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PROJECT COMPLETION REPORT

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Physicochemical Transformations within Ephemeral Streambeds
Related to Sewage Effluent Releases

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ABSTRACT

Hydraulic and physicochemical measurements were made on treated sewage effluent releases at established locations within the channel of an ephemeral stream, the Santa Cruz River of Southern Arizona. Water quality samples were taken in sequence so that incremental flows at different hydrograph stages could be traced as the effluent moved downstream. Hydrographs obtained from two H-L flumes were used to calibrate a modified kinematic wave model. Hydraulic parameters from the kinematic model and physicochemical measurements from water quality samples were combined together into a statistical-empirical kinetic model of nitrogen transformations which may occur in sewage effluent releases. There was fair agreement between the measured data and the nitrogen species values calculated with the model. Measured nitrogen species values indicated that the rate of nitrification in sewage effluent releases is related to flow distance and physical characteristics of the stream.

INTRODUCTION

Municipal wastewater is being produced at an ever-increasing rate in the arid southwest due to an increase in population. For example, in the Tucson region the wastewater level has increased from 12 mgd in 1955 to over 30 mgd in 1974.

The rate of production had increased sufficiently such that prior to 1970 there was considerable surplus of sewage effluent which could not be used on approximately 300 acres of city-owned agricultural land surrounding the sewage treatment plant and 1,200 acres of private land being irrigated under contract. Consequently, there was a substantial buildup in wastewater directly released to the river. Then, beginning in 1970, the 1,200 acres of private land was no longer irrigated and essentially all of the wastewater was, and has continued to be, released to the river. Consequently, increasing quantities of the effluent have been released to the channel of the Santa Cruz River. The resulting effluent is filtering through the streambed and into the groundwater supply -- the major supply of domestic water for Tucson. Water quality investigations done by Matlock, Davis, and Roth (1972) suggested that nitrates and other chemical constitutents in the groundwater supply need further investigation. Therefore, a study was initiated to obtain information on the water quality and quantity changes in sewage effluent releases flowing down in the ephemeral stream channel of the Santa Cruz River. This study should provide basic data for an overall nitrogen balance survey of the lower Santa Cruz groundwater basin and serve as a guide for improved management of this and similar effluent release areas in the Southwest.

Records of the City of Tucson Sewage Treatment Plant were examined for information concerning quantities and quality characteristics of the treated effluent released at the plant. In order to trace downstream reductions of flow by infiltration and other losses, two four-foot H-L flumes were installed near Cortaro Road, approximately six river miles downstream from the plant, and at Rillito Narrows near the Avra Valley Road crossing, approximately eleven river miles downstream. From these measurement locations, the sinusoidal hydrograph of sewage effluent releases showed a large daily advance and recession of the wetted front of effluent in both longitudinal and lateral directions of flow. The low ebb of surface flow was depleted and disappeared at a distance of about ten miles, and at peak flow the effluent extended down the river from the plant approximately twenty miles. Therefore, the physical environment of the sewage was exceedingly complicated by fluctuating flows, varying chemical constituents of the sewage and the regime of the dry Santa Cruz River.

Objectives of the Study

The overall objective of the project was to examine the various transformations occurring within a desert stream channel (the Santa Cruz River of Southern Arizona) during sewage effluent releases. Specific objectives were: (1) to characterize spatial and temporal changes in the physical and chemical composition of sewage effluent downstream, (2) to evaluate various mathematical models for prediction of sewage effluent hydrographs and nitrogen species transformations occurring at various downstream locations, and (3) compare actual and predicted values of sewage effluent hydrographs and nitrogen species transformations for specific models.

LITERATURE REVIEW

Review of Previous Studies Within Project Area

Disposal of secondary sewage effluent from the municipal sewage treatment plant was first used for irrigation on the City Sewer Farm and later sold for use on private lands. In 1964, during the reconstruction of an effluent canal, the total discharge of the City Sewage Treatment Plant was bypassed to the river channel. Measurements of the flow at that time showed an average infiltration rate of approximately 3 cfs/mile of river channel for a 6-mile reach downstream from the City Sewage Treatment Plant (Matlock, 1966). In addition, Matlock (1966) noted that the cyclic nature of the effluent discharge resulted in daily channel cleaning and the removal of material deposited at low flow periods. He also found that occasional flood flows increase infiltration rates and the recharge condition by scouring and moving deposited materials in the river channel.

Matlock (1965) studied the interrelationship of stream discharge and suspended sediment load on infiltration rates in Rillito Creek sediments. He found that infiltration rates in these sediments are proportional to stream velocity and inversely proportional to suspended sediment content. Marsh (1968) evaluated the effects of suspended sediment and stream discharge on infiltration rates in the Santa Cruz River. Recharge rates varied from 4.2 feet/day to 5.0 feet/day. In addition, he found that increasing discharge rates appeared to increase infiltration rates through the effect of stream velocity on bed erosion and sedimentation. He concluded that increasing suspended sediment concentrations reduced infiltration rates.

Burkham (1970a) developed a method for relating infiltration rates to streamflow rates for streams that are perched above the water table. He found that an equation based on the assumption that infiltration velocity is proportional to stream depth seems to correlate closely with infiltration rates during typical short-duration flows of ephemeral stream. Burkham (1970b) also made estimates of average annual volume of infiltration for the period 1936-1963 along seven normally dry alluvial channels in the Tucson basin. The general empirical relation used between inflow rates and infiltration rates for a reach of channel is:

$$\text{infiltration rate} = C\ (\text{inflow rate})^{0.8}$$

in which C is a variable coefficient.

Pennington (1970) conducted studies at the Tucson Sewage Treatment Plant on ammonia dissipation from secondary sewage effluent. He found that photosynthesis of algae caused a rise in pH resulting in a shift in the ammonia-ammonium equilibrium. He also found that total ammonia removal after 60 hours exceeds 70 percent, of which 13 percent was released to the atmosphere.

Cluff, DeCook and Matlock (1972) made an investigation of the feasibility of exchanging sewage effluent for groundwater being used for irrigation. They also monitored the downstream reduction of sewage effluent flow in the Santa Cruz River channel caused by infiltration and evapotranspiration. A summary of average infiltration rates indicates that a rate of 3.0 cfs/mile occurred between Cortaro Road and the Rillito Narrows near Avra Valley Road. In this reach, they note, there is a reduced stream gradient with a corresponding increased channel width which causes larger variations of wetted area between high and low sewage effluent flows; the changes in wetted area in turn tend to increase the infiltration rate due to the drying of the otherwise anaerobic organic deposits. They conclude that a buildup of organic deposts in the streambed decreases the infiltration rate significantly. They measured nitrogen species transformations occurring in sewage effluent as it proceeded downstream and noted that total nitrogen content decreased fairly consistently with flow distance. Changes in measured organic nitrogen content were relatively minor. However, there was a pronounced and persistent decrease in ammonia-nitrogen in the downstream direction. Correspondingly, there was a gradual increase in nitrate-nitrogen, indicating nitrification, notably below Cortaro Road where aeration is enhanced due to a wider surface area. In addition, it was hypothesized that the denitrification process may occur in the layered organic deposits described earlier.

Additional effluent flow studies were made by Sebenik, Cluff, and DeCook (1972), in which it was found that average infiltration rates of approximately 3.0 cfs/mile occurred in an 11-mile reach of stream channel. This study also included analysis of nitrogen transformations in the effluent flow showing that the rate of nitrification was related to flow distance and physical characteristics of the stream channel, with both nitrification and denitrification processes evidently occurring in the same moving effluent stream profile. Total nitrogen was usually below 20 mg/l; it decreased with distance, particularly during high flow periods.

Wilson and Small (1973) measured sewage effluent flows between two stations within the project area and found that discharge rates range between 32 cfs and 52 cfs. They also noted that the infiltration rates ranged from 1.5 ft/day to 7.7 ft/day with an average infiltration rate of 36.4 acre-ft/day per mile of river channel.

Kinematic Flow Approach

The kinematic wave approach was chosen to model the sinusoidal effluent wave down the dry Santa Cruz River because it is reasonably accurate and easy to compute using high-speed computers. The routing of the channel flow can be done by the solution of the equations of continuity and motion as shown by Woolhiser and Liggett (1967):

a. Equation of continuity:

$$\frac{\partial A}{\partial t} + \frac{\partial (AV)}{\partial x} = q$$

b. Equation of motion:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{\partial}{A}\ \frac{\partial(A\bar{y})}{\partial x} + \frac{Vg}{A} = g\ (S_0 - S_f)$$

in which V = mean flow velocity,
h = depth of flow,
$\bar{y}$ = depth to the center of gravity of the cross-sectional area,
A = area of cross-section of flow,
g = acceleration of gravity,
q = lateral inflow rate,
S_0 = bottom slope, and
S_f = slope of the energy line.

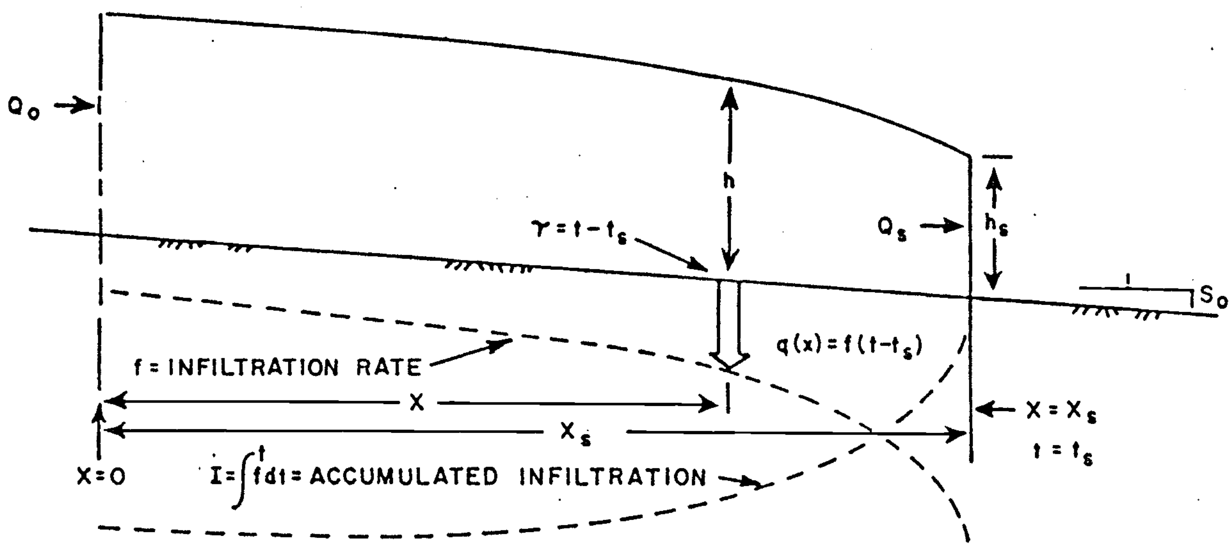
Smith (1972) made a major contribution to kinematic modelling by using kinematic wave approximations in conjunction with Chezy's formula and a point infiltration equation to arrive at a method of predicting advance rate, surface profiles and modifications with time to kinematic wave flow over an initially dry infiltrating plane. As shown in Figure 1, a flow of $Q_0(+)$ begins at X = 0 at time t = 0. The wave front is assumed to travel as a kinematic shock or flow discontinuity which moves with a velocity $V_s(x) = \frac{\Delta Q}{\Delta h}$ in which ΔQ and Δh are change in discharge and depth, respectively, across the shock. This reduces to Q_s/h_s when the initial depth and flow are zero, where h_s and Q_s are depth and flow rate immediately behind the shock. Point infiltration is a function of time since the shock passed the point and, thus, is dependent on time and shock velocity.

Smith (ibid.) also suggested that a similar technique is applicable for flood wave movement and attenuation in dry alluvial channels. Therefore, Smith's kinematic wave approximation model, as discussed later, was used to determine the effluent flow hydrographs at various locations.

Nitrogen Cycle

A general overview of the major features of the nitrogen cycle and its components needed in this study are shown in Figure 2. The nitrogen cycle is initiated at the point where organic nitrogen (amines, nitrites, proteins) and ammonia originating in municipal and industrial waters are discharged into a water body.

The organic nitrogen undergoes an hydrolytic reaction producting ammonia as one of the end products, which, in addition to the ammonia present in the wastewaters, provides a food source for the nitrifying bacteria. The oxidation process proceeds sequentially from ammonia through nitrite to nitrate.



Where:

t = time

t_s = time of initial wetting

$t > t_s$ = means that infiltration occurs

$t < t_s$ = means that no infiltration occurs

Υ = time since ponding of the surface area

x = distance along channel

x_s = point of initial wetting

Figure 1. Definition Sketch for Kinematic Shock Wave Advance on Infiltrating Plane. -- After Smith, 1972.

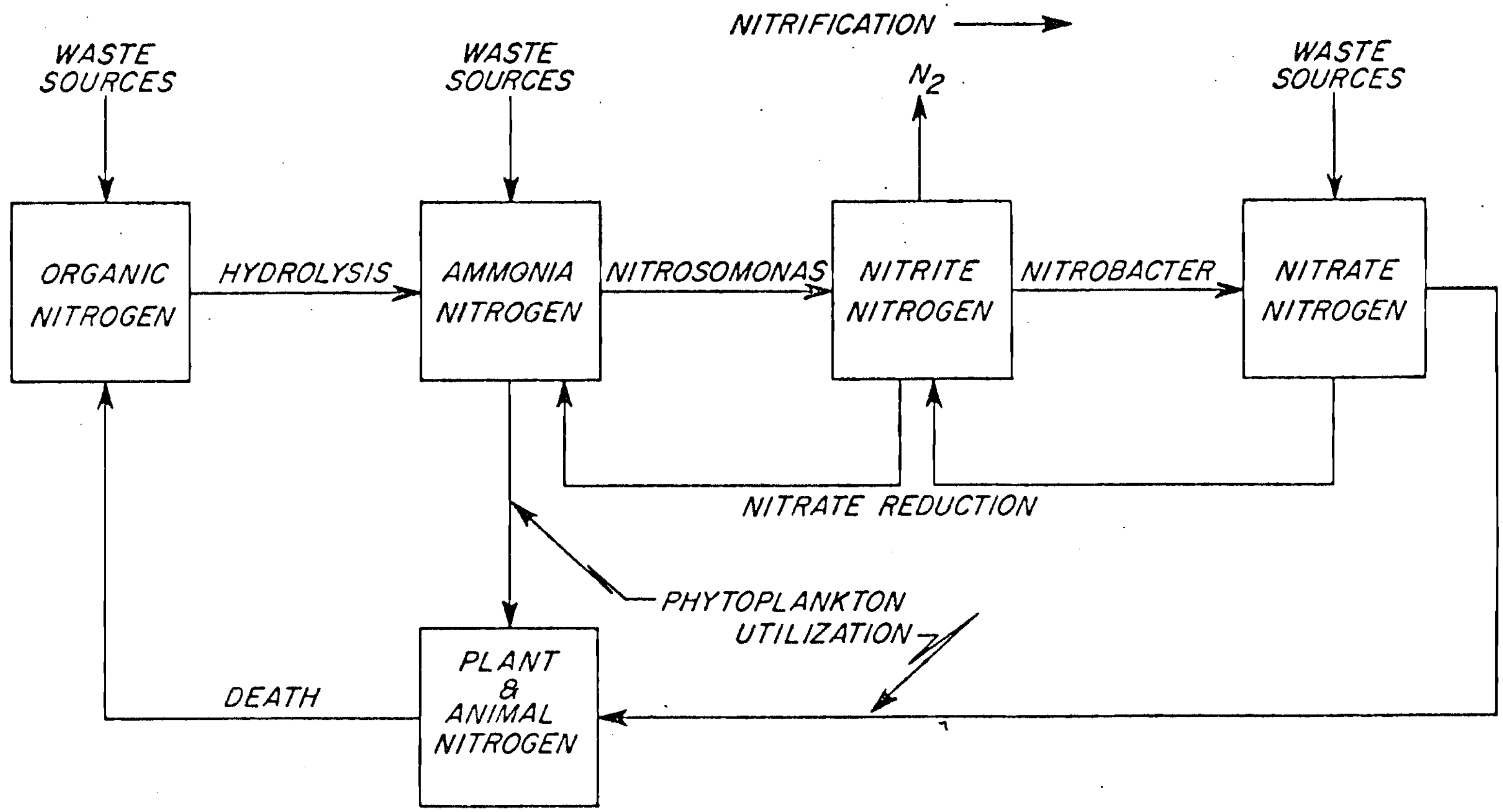


Figure 2. Major Features of the Nitrogen Cycle. -- After O'Connor, Thomann and DiToro (1973).

There are two broad areas of concern from the water quality viewpoint with respect to the nitrogen cycle in natural waters: (1) the oxidation and possible reduction of various forms of nitrogen by bacteria and the associated utilization of oxygen, and (2) the assimilation of the inorganic nitrogen and the release of organic nitrogen by phytoplankton during growth and death, respectively (O'Connor, Thomann and DiToro, 1973).

Modeling the Nitrification Process

The modeling of the nitrification process whereby ammonium ions are changed into nitrate ions through biochemical action has been attempted over many years by numerous authors. The modeling process involves two cornerstones of physical chemistry -- thermodynamics and kinetics. The equilibrium situation is described by the laws and equations of thermodynamics, while the rate at which the system is moving toward a given condition is described by the formulation of kinetics. Yet, the biogenic systems, such as nitrogen cycle, are the most obvious examples of nonequilibrium distributions which require a kinetic approach. Since nitrogen transformations usually proceed at a slow rate and these reaction rates depend upon the nature of the reactants, a modified kinetic approach was selected.

The nitrification process is an autotrophic biochemical reaction in which the energy for the growth of the microorganisms is obtained from the oxidation of ammonia or nitrite. As noted by Lawrence and McCarty (1970), the rate is generally assumed to be proportional to the concentration of the substrate and also of the microorganisms. The growth equation for the microorganisms may be written as:

$$\frac{dM}{dt} = KM$$

where M is the microbial concentration and K is the microbial growth coefficient, as given by Pearson (1968). Therefore, consecutive-type kinetics are frequently used to describe change in nitrogen forms in wastes flowing through trickling filters, in rivers or estuaries downstream from waste discharge, or in agricultural soil with fertilizer and irrigation applications.

FACILITIES AND EQUIPMENT

Project Area

The project area (Figure 3) lies within the floodplain of the Santa Cruz River, an ephemeral stream, located in Southern Arizona, near Tucson, and extends from the Tucson Sewage Treatment Plant to a bedrock constriction which is locally known as the "Rillito Narrows," eleven miles downstream.

Characteristics of Stream Channel

The stream channel is entrenched with stream alluvium of unconsolidated clay, silt, sand and gravel, which is from 20 to more than 100 feet thick. During periods of no flow, the alluvium within the streambeds normally is

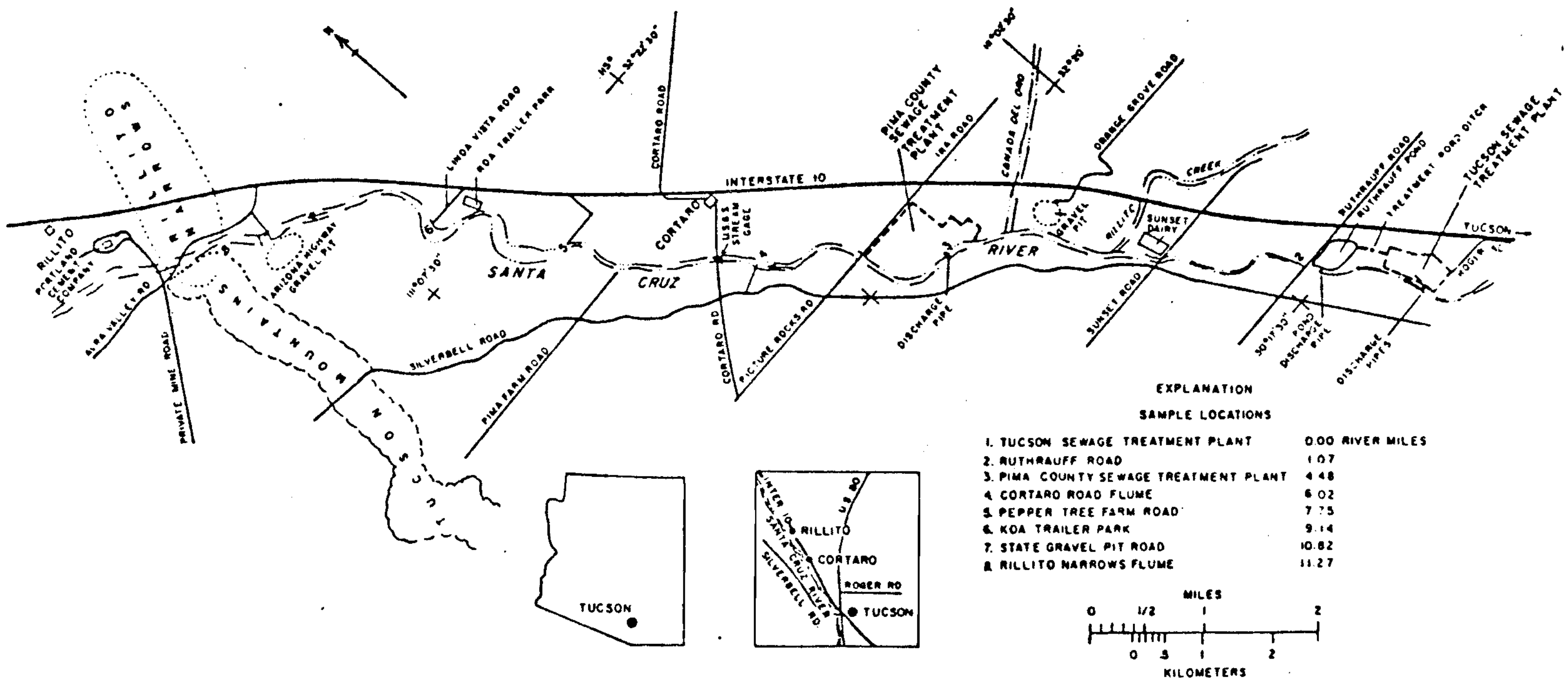


Figure 3. Location Map of Project Area.

stratified clay, sand and silt on the surface. However, during flow periods caused by direct rainfall, storm runoff peaks averaging 3,000 cfs (Condes de la Torre, 1970) cause a rapid turnover and mixing of stratified sediments with either net erosion or sedimentation occurring. Naturally, increased infiltration occurs after these storm runoff periods due to cleaning and scouring action.

Bypass Channel and H-L Steel Flume Construction

Two water measurement sites were selected along the Santa Cruz River, the first near Cortaro Road, 6.02 river miles downstream from Tucson Sewage Treatment Plant (TSTP), and the second at Rillito Narrows near Avra Valley Road, 11.27 river miles downstream from TSTP. In June, 1972, small cuts at both locations were excavated into the stream bank. A four-foot, H-L flume, with automatic stage recorder, as adapted from Holtan, Minshall and Harrold (1962), were assembled and installed within the excavations (see Figure 4).

The flumes were installed at the end of a bypass channel excavated upstream and parallel to the main stream channel, so that approximately twenty-five feet of grassy bank separated the bypass channel from the main channel. The bank provided a margin of safety from floods. The schematic drawing of the bypass channel, H-L flume and river channel is shown in Figure 5.

TSTP Discharge Facilities

The TSTP has five main transportation system points which eventually discharge sewage effluent into the Santa Cruz River. These waste water transportation system points are the following:

1. Plants 1 and 2, measured by a three-foot Parshall flume bypassed into a drop inlet which connects to a three-foot diameter concrete pipe extending to the Santa Cruz River.

2. Plant 3, measured by a 3-ft Parshall flume bypassed into a drop inlet which connects to a 3-ft diameter concrete pipe extending to the Santa Cruz River.

3. Ruthrauff Pond Canal which takes high peak sewage flows from both measured points to Ruthrauff Road holding pond which is approximately 0.25 miles from TSTP.

4. Sludge pipe from anaerobic digesters to the Ruthrauff Road Pond Canal which bypasses the measured control sections.

5. Ruthrauff Road holding pond, containing about 380 acre-ffet of sewage effluent, has concrete drain pipes and a concrete spillway which may also release sewage effluent to the Santa Cruz River.

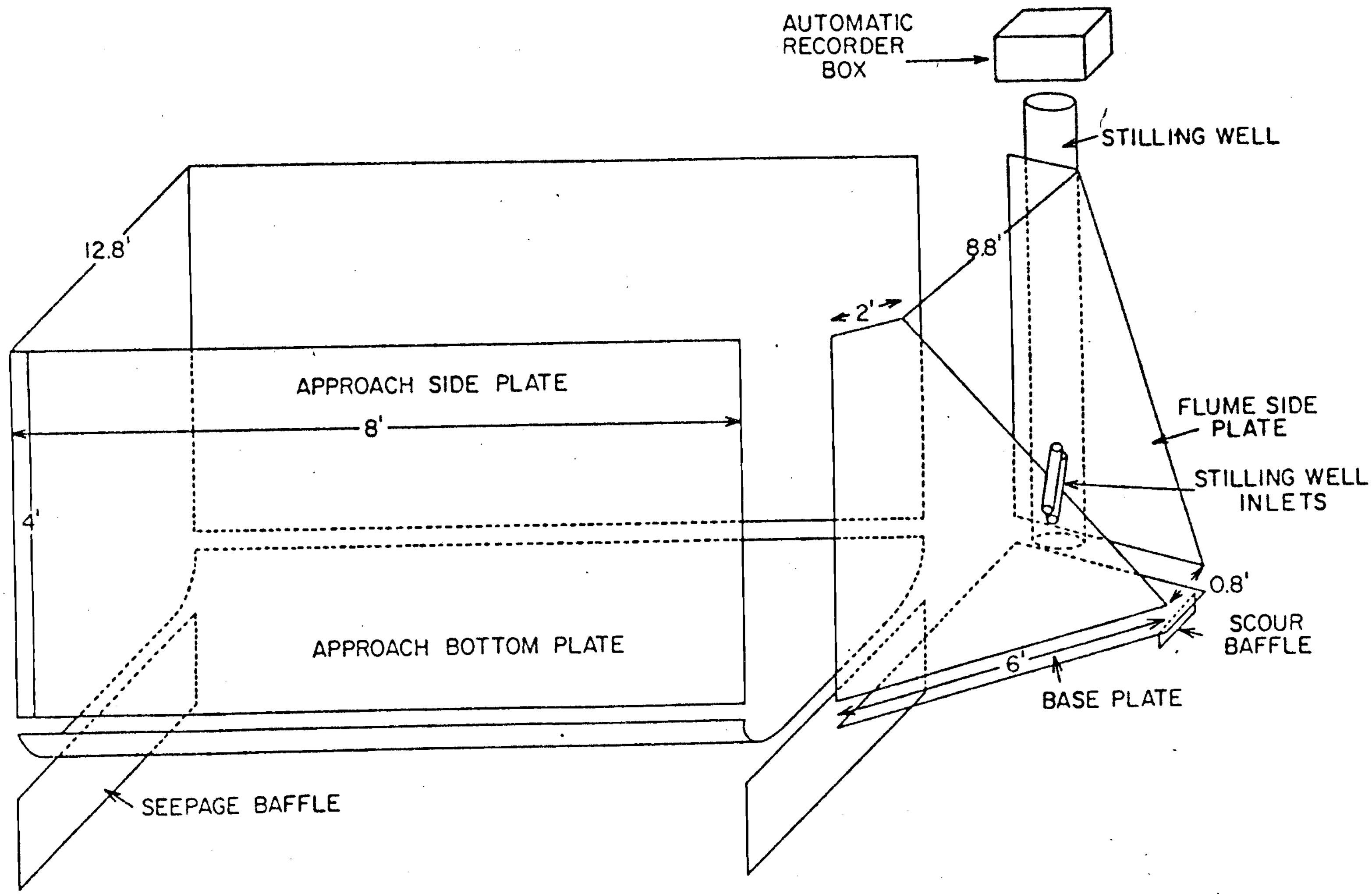


Figure 4. Scale Drawing of the Steel H-L Flume and Automatic Recorder Installation.

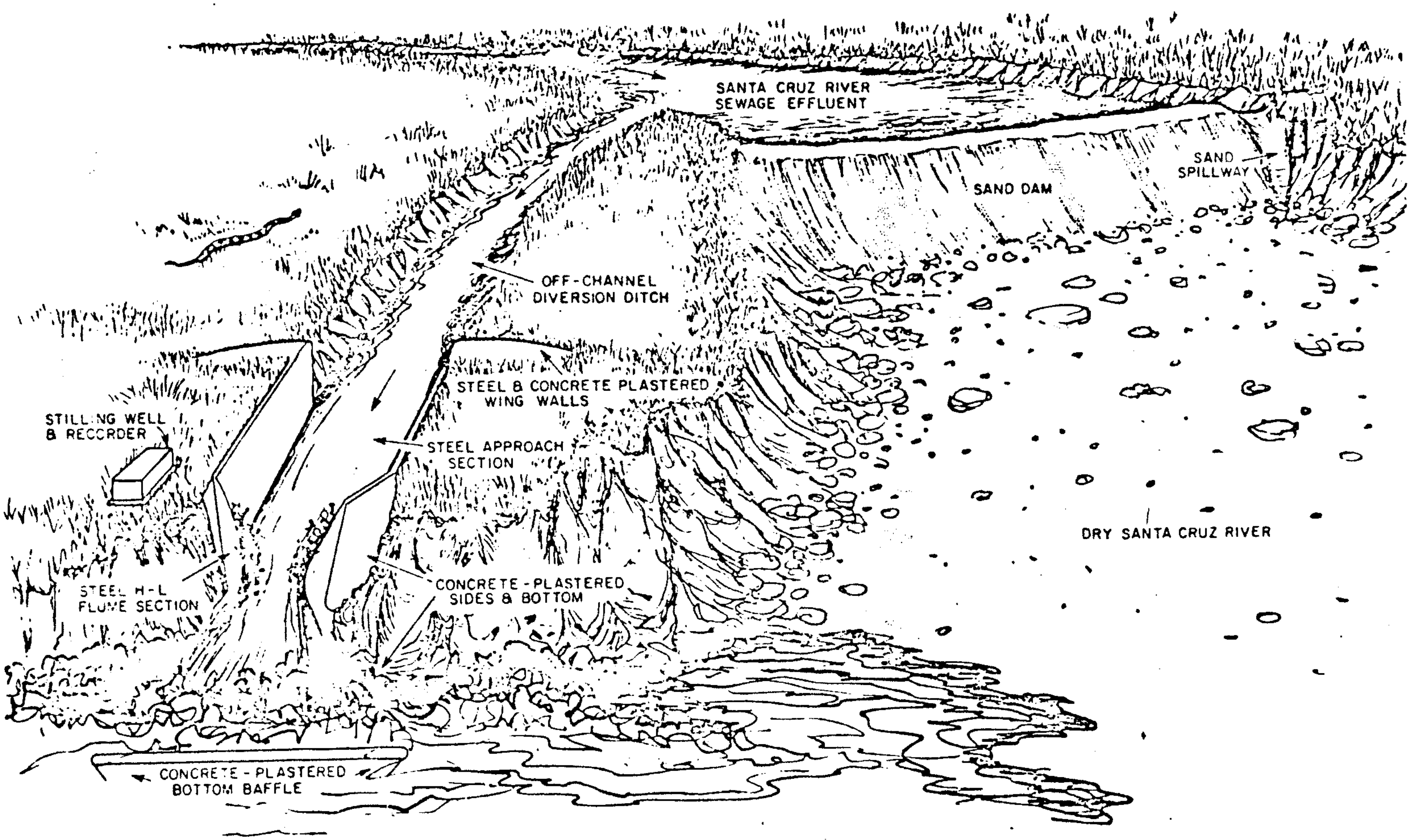


Figure 5. Typical Drawing of Effluent Flow Measurement Station.

During the study period, which began on May 30, 1973, and ended July 10, 1973, both Parshall flumes were measuring sewage flows to the river. Every day during the sampling period, a portion of the high flow peaks was diverted down the Ruthrauff Pond ditch; however, on certain selected days a large quantity of the total sewage effluent releases was also diverted down the canal to maintain a full volume of sewage effluent within a Ruthrauff Road Pond. In order to measure diverted quantities in the canal, a stilling well, with automatic stage recorder, was installed adjacent to the canal near the inlet to Ruthrauff Pond. A rating curve was then prepared for the particular trapezoidal section of the canal. With this measurement, all quantities of sewage effluent diverted into the river could be determined.

PCSTP Discharge Facilities

The PCSTP is a series of oxidation ponds totaling ten acres near Ina Road, about 12 miles northwest of Tucson, or approximately 5 miles downstream from TSTP. The lagoon site is located on the flood plain of the nearby Santa Cruz River with a one-foot diameter outlet pipe protruding from the streambank and discharging about 1.5 cfs of effluent constantly from lagoon into the river channel. This additional effluent discharge was also tested during the sampling period.

EXPERIMENTAL PROCEDURES

Preliminary Flow Data

Preliminary discharge records from TSTP were analyzed in conjunction with Cortaro and Rillito Narrows flume data before the sampling period, May 30 to July 10, 1973, to establish effluent hydrograph conditions at various locations downstream. During the sampling period, all effluent flow records from Plants 1 and 2, Plant 3, Ruthrauff Pond Canal, Cortaro Road flume and Rillito Narrows flume were measured constantly and rechecked for accuracy. Sewage effluent hydrographs from the three permanent locations were plotted and the various water flow travel times for given discharge rates from TSTP were determined by graphical methods. From these travel times, a given discharge quantity of effluent with a known chemical concentration could be sampled at any other locations as it proceeded downstream.

Stream Profiles

Before and after the sampling period, a stream survey was made by stadia rod to determine the exact cross-section, water depth, water width and wetted area of various representative stream sections to establish basic data for the kinematic wave model. The cross-sections were tied to a benchmark by leveling.

The sections were selected so that there was a nearly uniform cross-section between two stations. It was determined that between TSTP and Ina Road (approximately 5 river miles downstream) stream sections of one-mile increments would be satisfactory. However, between Ina Road and Rillito Narrows flume (11.27 river miles downstream), stream section at half-mile intervals were selected. In addition, between Ina Road and Pepper Tree Farm Road (7.75 river miles downstream), supplemental surveys were done to reflect radical changes in stream cross-sectional area.

Water Quality Sampling

Water quality sampling schedule is summarized in Table 1: (1) five sampling periods represent various conditions during the overall sampling program, (2) five sampling times within each sampling period reflect the characteristic points of the discharge hydrograph, and (3) eight sampling locations during the sampling period were selected to maximize the accurate determination of nitrogen species transformations in a flow parcel os sewage effluent as it proceeded downstream. No water quality sample locations were selected between Ruthrauff Road and Cortaro Road because previous studies of nitrogen transformations indicated that little or no overall nitrogen transformations, especially nitirifcation, in this reach occurred (Sebenik et al., 1972), and the channel had similar hydraulic parameters.

Water quality samples were collected at the eight established stations as the effluent proceeded downstream by taking three integrated grab samples in one-liter sample bottles. These integrated samples were taken in the middle of the effluent flow and were filled through the entire water depth profile. Extra care was then taken in sampling during high peak flows. After effluent samples were taken, one of the sample bottles, appropriately marked, had forty milligrams (mg) of mercuric chloride ($HgCl_2$) solution added to prevent any further microbial action which would cause extreme errors in various chemical constituents. In addition, all samples were placed in an ice-packed thermal chest to further inhibit chemical changes.

Chemical Analysis

Field Analysis

Three physicochemical parameters were analyzed at every sampling time so that actual field conditions could be determined. These three parameters were: (1) temperature (^{o}C), (2) pH, and (3) dissolved oxygen content (mg/l). Portable dissolved oxygen and pH meters were used in the field. Before and sometimes during each sampling periods, each meter was carefully calibrated and rechecked for accuracy.

Laboratory Analysis

All chemical analyses of the sewage effluent were conducted as described in the American Public Health Association's Standard Methods (1971). The first analysis stage consisted of measuring the following physicochemical parameters: (1) pH, (2) temperature (^{o}C), (3) chemical oxygen demand (mg/l),

Table 1. Water Quality Sampling Schedule.

Number	Sampling Periods	Sampling Times at the TSTP	Locations
1	June 9-10, 1973	0730 -- Low Flow	Tucson Sewage Treatment Plant (TSTP) 0.00 river miles downstream
2	June 22-23, 1973	1000 -- Rising Limb	Ruthrauff Road (RRR) 1.07 river miles downstream
3	June 26-27, 1973	1430 -- Primary High Flow	Pima County Sewage Treatment Plant (PCSTP) 4.48 river miles downstream
4	July 3-4, 1973	2100 -- Secondary High Flow	Cortaro Road Flume (CRF) 6.02 river miles downstream
5	July 5-6, 1973	0400 -- Declining Limb	Pepper Tree Farm Road (PTF) 7.75 river miles downstream
6			Near KOA Trailer Park (KOA) 9.14 river miles downstream
7			State Gravel Pit Road (GPS) 10.82 river miles downstream
8			Rillito Narrows Flume (RNF) 11.27 river miles downstream

and (4) conductivity (Mmhos). The second analysis stage consisted of measuring the nitrogen species: (1) organic nitrogen (ORGN, mg/l), (2) ammonia nitrogen (NH_3N, mg/l), and (3) nitrite-nitrate nitrogen ($NO_2N + NO_3N$, mg/l). The third analysis stage consisted of measuring: (1) total alkalinity or carbonate ($CO_3^=$, mg/l) and bicarbonate (HCO_3^-, mg/l), (2) chloride (Cl^-, mg/l), (3) suspended solids (mg/l), and (4) total solids (mg/l). All analyses of samples were completed within a forty-eight hour periods after being collected.

DEVELOPMENT OF SEWAGE EFFLUENT FLOW MODEL

Basic Kinematic-Wave Model

A digital computer simulation model was developed by Smith (1972) to model a kinematic-wave flow over an initially dry infiltrating plane, using a single step Lax-Wendroff numerical solution. The basic equations of the model were derived from three differential equations -- continuity, kinematic description of stage-discharge relationship, and infiltration rates from a ponded surface. The kinematic-wave model was then adapted by Smith to simulate a kinematic-wave through an infiltrating trapezoidal channel of variable dimensions, which reflected the unusual hydraulic conditions of sewage effluent releases in the Santa Cruz River.

Effluent Flow Model Revisions

The kinematic-wave model previously discussed was modified due to the skewed sinusoidal pettern of effluent releases and high evaporation from the water surface. The effluent releases caused a large daily variation of the wetted area in the downstream and across stream directions. High evaporation rates occurred during sampling periods due to a combination of high temperature and large surface area at high flow peaks. Therefore, a correction equation was used in the model to simulate these two factors.

An additional correction was also made for the steady discharge of 1.5 cfs from the Pima County Sewage Treatment Plant (PCSTP), 4 miles downstream from the origin. This small amount of effluent was added constantly to the kinematic-wave as it passed the PCSTP discharge point; however, this flow did not influence the flood wave progression to any appreciable degree.

NITROGEN TRANSFORMATION MODEL

Hydraulic and Physicochemical Pathways

The bio-physicochemical model of Dutt et al. (1970) previously discussed as used as a guide to predict various chemical transformations as sewage effluent proceeds downstream. Nitrogen transformations were emphasized in the model, since they represent a major biochemical transformation pathway in sewage effluent and may be a contributing factor to the excessive nitrate concentration in the groundwater supply northwest of Tucson. As shown in Figure 6, the major nitrogen transformation pathways selected were ammonification of organic nitrogen, ammonia volatilization, ammonia immobilized, ammonia incorporated, and nitrification.

Development of Equations

Most nitrogen transformations in waters usually proceed too slowly to be approximated by equilibrium relationships (Shaffer, 1970). Therefore, a statistical kinetics approach was selected to model the pathways, to simplify the structure of the model and to provide a rapid numerical solution. Each pathway was quantified by a rate equation using computerized multiple regression analyses of the chemical parameters examined during the study and the predicted hydraulic parameters using data from the first three sampling days. The rate euqations were then used to predict the nitrogen transformations occurring the last two sampling days.

General Chemical Reaction Rates

The reaction rate (K) for each nitrogen pathway was selected and then combined as follows:

$$\begin{tikzcd} & & \text{Ammonia Nitrogen Loss} \\ \text{Organic Nitrogen} \arrow[r, "K_1"'] & \text{Ammonia Nitrogen} \arrow[ur, "K_3"] \arrow[rr, "K_2"'] & & \text{Nitrate Nitrogen} \end{tikzcd}$$

where $\frac{d\ ORGN}{dt} = -K_1$

$$\frac{d\ NO_3N}{dt} = K_2 - K_3$$

$$\frac{d\ NH_3\text{-}N}{dt} = K_1 - K_2 - K_3$$

The ammonification and nitrification processes are consecutive reactions where the products of one reaction become the reactant to the following reaction. Then a solution for concentrations of each constituent at the same time is as follows:

Organic nitrogen concentration (C_n)

$= $ Organic nitrogen concentration $(C_0) - K_1\Delta t$

Ammonia nitrogen concentration $(C_n) - K_2\Delta t - K_3\Delta t + K_1\Delta t$

$= $ Ammonia nitrogen concentration (C_0)

Nitrate nitrogen concentration (C_n)

$= $ Nitrate nitrogen concentration $(C_0) + K_2\Delta t - K_3\Delta t$

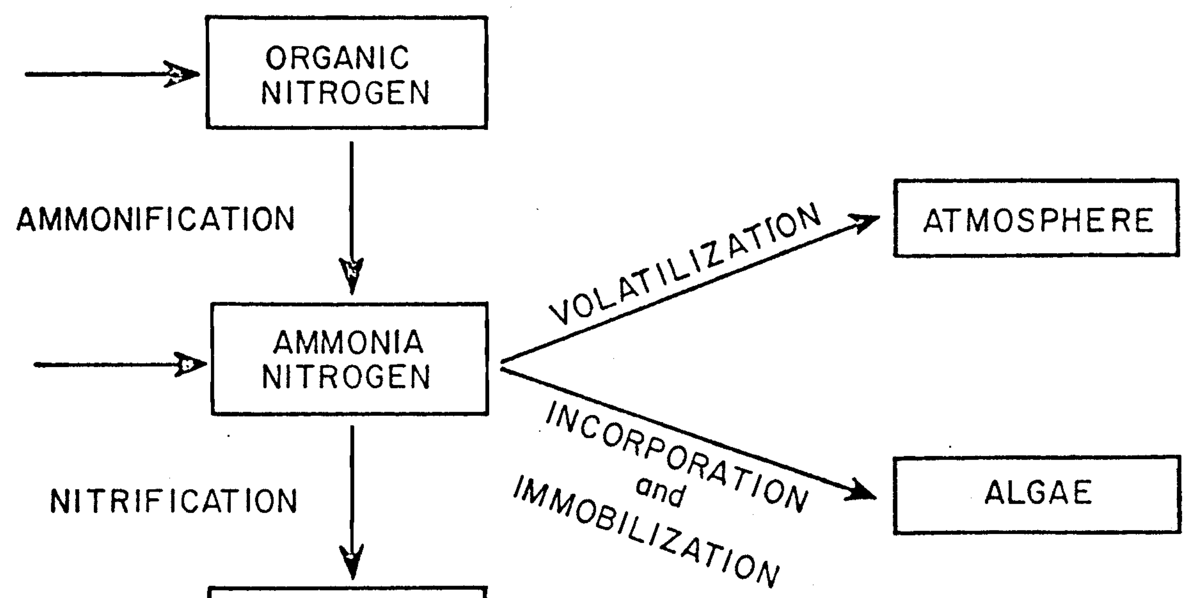


Figure 6. Biochemical Pathways Within Nitrogen Transformation Model.

where C_0 = initial concentration (mg/l),

C_n = predicted concentration (mg/l) of appropriate nitrogen species,

$\Delta t = t_2 - t_1$ = sampling time interval (hours), and

K = reaction rates as function of time interval.

It is assumed that K_1, K_2 and K_3 are constant within time interval Δt but do vary from interval to interval depending upon certain conditions discussed later.

Ammonification Rate Equation

The basic independent variables in the final ammonification rate equation were ammonia-N (mg/l), cross-sectional area (ft^2), distance downstream (miles), and width of water surface (ft), travel time (hr), suspended solids (mg/l), and chlorides (mg/l). Other potential parameters were excluded for their low correlation coefficient values, lack of contribution to fit, direct dependence with other selected variables, or illogical use. The rate units for this and all other rate equations used in the model were expressed in milligrams per liter per hour (mg/l/hr).

The equation formed from the variables and coefficients described in TAble 2 represented the best fit obtainable in a reasonable length of time using data from the study of hundreds of variable combinations and numerous stepwise regression analyses.

Nitrification Rate Equation

The nitrification equation from Table 2 represented the net transformation of ammonia-nitrogen to nitrate-nitrogen. Additional pathways were either combined or included in the equation as follows: (1) nitrite-N to nitrate-N pathway which assumed nitrite-N concentrations were small and were directly converted to nitrate-N, (2) ammonia-N volatilization loss occurred at 0.065 per hour (Stratton, 1968) and (3) ammonia-N immobilization loss occurred at 0.00083 per hour which was an insignificant variable. However, the net result always was assumed to be the appearance of nitrate-N. The basic variables used to develop the equations were nitrate-N (mg/l), distance downstream (miles), travel time (hr), ammonia-N (mg/l), chemical oxygen demand (mg/l), pH, and velocity (ft/sec). Other

Table 2. Variables, Constants, and Statistical Tests for the Ammonification and Nitrification Rate Equations.

Time in hours.
Travel Time = Sample Time - Initial Time.
Chemical Concentration (mg/l).
(TSTP) = Initial concentration at TSTP.
NH_3N = Ammonia nitrogen concentration (mg/l).
NO_3N = Nitrite-nitrate nitrogen concentration (mg/l).
SEE = Standard error of the estimate.
F Ratio = Variance ratio of the means by the individual samples.

Distance in miles.
Sampling Time in hours.
Loss Rate = exp. (0.065 · ΔSampling Time).
(PCSTP) = Initial concentration at PCSTP.
ORGN = Organic nitrogen concentration (mg/l).
ΔNH_3N = Ammonia nitrogen concentration change (mg/l).
R^2 = Coefficient of determination.

Equation		Ammonification	Nitrification
Variable:	x_1	Travel Time · $LOG_{10}NH_3N$	Distance
Coefficient:	b_1	$-3.113 \cdot 10^{-2}$	$+4.209 \cdot 10^{-2}$
Variable:	x_2	$\Delta NH_3N/\Delta$Sampling Time	Travel Time · NH_3N(PCSTP) · Loss Rate
Coefficient:	b_2	$-2.258 \cdot 10^{-1}$	$-1.114 \cdot 10^{-2}$
Variable:	x_3	Cross-Sectional Area · ORGN	Travel Time · $LOG_{10}NH_3N$
Coefficient:	b_3	$+8.405 \cdot 10^{-3}$	$+2.374 \cdot 10^{-1}$
Variable:	x_4	ORGN(TSTP)	LOG_{10} Chemical Oxygen Demand
Coefficient:	b_4	$-8.114 \cdot 10^{-1}$	$-5.185 \cdot 10^{-1}$

Variable:	x_5	Suspended Solids	pH · NO_3N
Coefficient:	b_5	$1.956 \cdot 10^{-2}$	$+7.342 \cdot 10^{-2}$
Variable:	x_6	Chloride	LOG_{10} NH_3N(TSTP)/NO_3N(TSTP)
Coefficient:	b_6	$1.087 \cdot 10^{-1}$	$+5.346 \cdot 10^{-1}$
Variable:	x_7	[3.0 - Travel Time] · ORGN(PCSTP)	Velocity
Coefficient:	b_7	$-5.409 \cdot 10^{-2}$	$1.044 \cdot 10^{0}$
Variable:	x_8	Distance	Travel Time · NH_3N(TSTP) · Loss Rate
Coefficient:	b_8	$-4.366 \cdot 10^{-1}$	$-4.563 \cdot 10^{-3}$
Constant:		$-1.854 \cdot 10^{-1}$	$4.852 \cdot 10^{-1}$
F Ratio:		$5.76 \cdot 10^{0}$	$1.58 \cdot 10^{1}$
R^2 Value:		$3.68 \cdot 10^{-1}$	$5.84 \cdot 10^{-1}$
SEE:		$3.01 \cdot 10^{0}$	$6.97 \cdot 10^{-1}$

basic variables and transformations such as temperature were excluded because of their correlation values, lack of contribution to fit, or illogical use of variable.

Ammonia-Nitrogen Equation

Predicted ammonia nitrogen concentration for each succeeding time interval was calculated by the difference between ammonification rate equation and the nitrification rate equation, excluding the ammonia volatilization variables, which gave a rate of ammonia-N change between time intervals. The predicted ammonia nitrogen concentration at the given time interval was then lowered to account for ammonia volatilization loss. This technique was used to insure that ammonia loss was calculated accurately and not in conflict with the other two rate equations.

Computer Program

The basic rate equations were derived independently and had to be solved as a unit before any predicted output could be obtained. The method selected was particularly well suited to a high-speed digital computer. For convenience, an overall basic time interval were caused by different sampling times. This meant that both input and outputs from the rate equation depended upon the sampling time.

A generalized block diagram of the computer model is shown in Figure 7. The program consisted of six small primary sections: (1) inputsection, (2) initial condition section, (3) time interval section, (4) nitrogen transformation section, (5) nitrogen species output section, and (6) statistical output section. All nitrogen transformation sections were dependent on both the initial hydraulic and chemical species conditions and parameters as well as the specific form of nitrogen concerned.

Correction and Verification

After the program was constructed, its predicted output was compared with observed data from the first sample day. It was noted that predicted organic-N and nitrate-N concentrations were extremely high on the initial computer trials. High predicted values could be either caused by high initial chemical values at PTSTP and TSTP or extreme hydraulic values at selected stream sections, which, in turn, would cause an overestimation of reaction rates due to settling and coagulation properties of suspended solids in combination with organic materials found in sewage effluent. As a correction, the predicted ammonification rate was reduced when a suspended solid concentration greater than 200 mg/l was measured at PCSTP. The predicted nitrification was also retarded in periods of high flow and high pH values. Therefore, a corrective constant for both conditions of ammonification and nitrification were included to account for these anomalies.

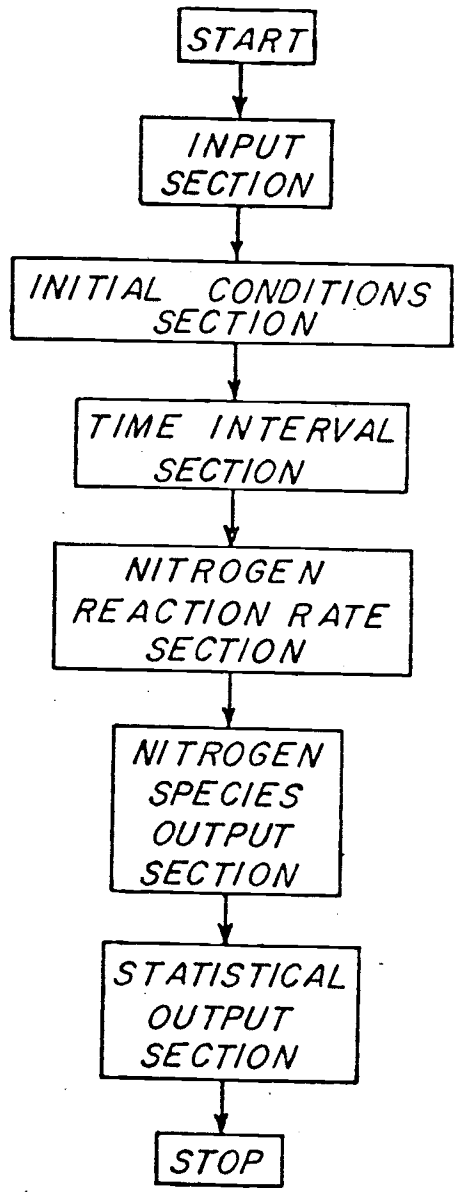


Figure 7. Generalized Block Diagram of the Computer Program.

RESULTS AND DISCUSSION

Hydraulic Parameters

The modified kinematic-wave model was used to simulate the sewage effluent flow hydrographs at both flume locations -- Cortaro Road and Rillito Narrows -- on five sample periods: (1) sample period June 9-10, 1973; (2) sample period June 22-23, 1973; (3) sample period June 26-27, 1973; (4) sample period July 3-4, 1973; and (5) sample period July 5-6, 1973. Included within the hydraulic model, a modified infiltration formula was used to account for channel losses, and is shown as follows:

$$F = 0.5 + 1.0\ (T - T_0)^{-0.60} - f' - E$$

where F = overall infiltration rate (in/hr),
T_0 = initial time of surface wetting (hr),
T = sample time (hr),
F' = wetting area coefficient (in/hr), and
E = evaporation rate (in/hr).

As shown in Figure 8, the sinusoidal properties of the simulated and measured flows at both stations throughout the sample day were extremely consistent. The rising and falling limbs of the simulated flows at Cortaro Road coincided exactly with measured flows. The simulated flows at Cortaro Road had slightly larger peaks and slightly lower troughs compared with measured flows. The errors in the extreme points of the simulated hydrograph at Cortaro Road were probably caused by overestimating infiltration rates during low flow and underestimating infiltration rates during high flows. It is further complicated by the kinematic-wave model which averages the temporal and spatial units into approximately five-minute intervals and 900-foot stream sections, thus causing an averaging of infiltration rates. Other possible factors causing infiltration rate errors could be: (1) unaccounted-for riparian transpiration at various stream sections, (2) algae and streambed deposits, (3) velocity of water, discharge volume and infiltration rate relationships, which are probably the most critical factors in alluvial channels.

At Rillito Narrows, the simulated flow hydrograph has a faster rate of increase in the rising limb of the hydrograph and a faster rate of decrease in the declining limb compared with measured flows. The simulated flow has an earlier initial and final time of wetting as well as slightly larger peak flow. The disparity between measured and simulated flow hydrographs at Rillito Narrows may be caused by two conditions: (1) the use of a constant Chezy coefficient (40.0) throughout the entire eleven-mile stream reach, and (2) the possibility of clogging and silting of the flume's stilling well inlet by microbial, organic and streambed deposits during different hydrograph stages.

In Figure 9, the sewage effluent flow hydrograph of the second sampling period (June 22-23, 1973) is presented as a representative example of the verification run for the kinematic-wave model. Figure 9 again shows the excellent agreement between the measured and simulated flows at both locations.

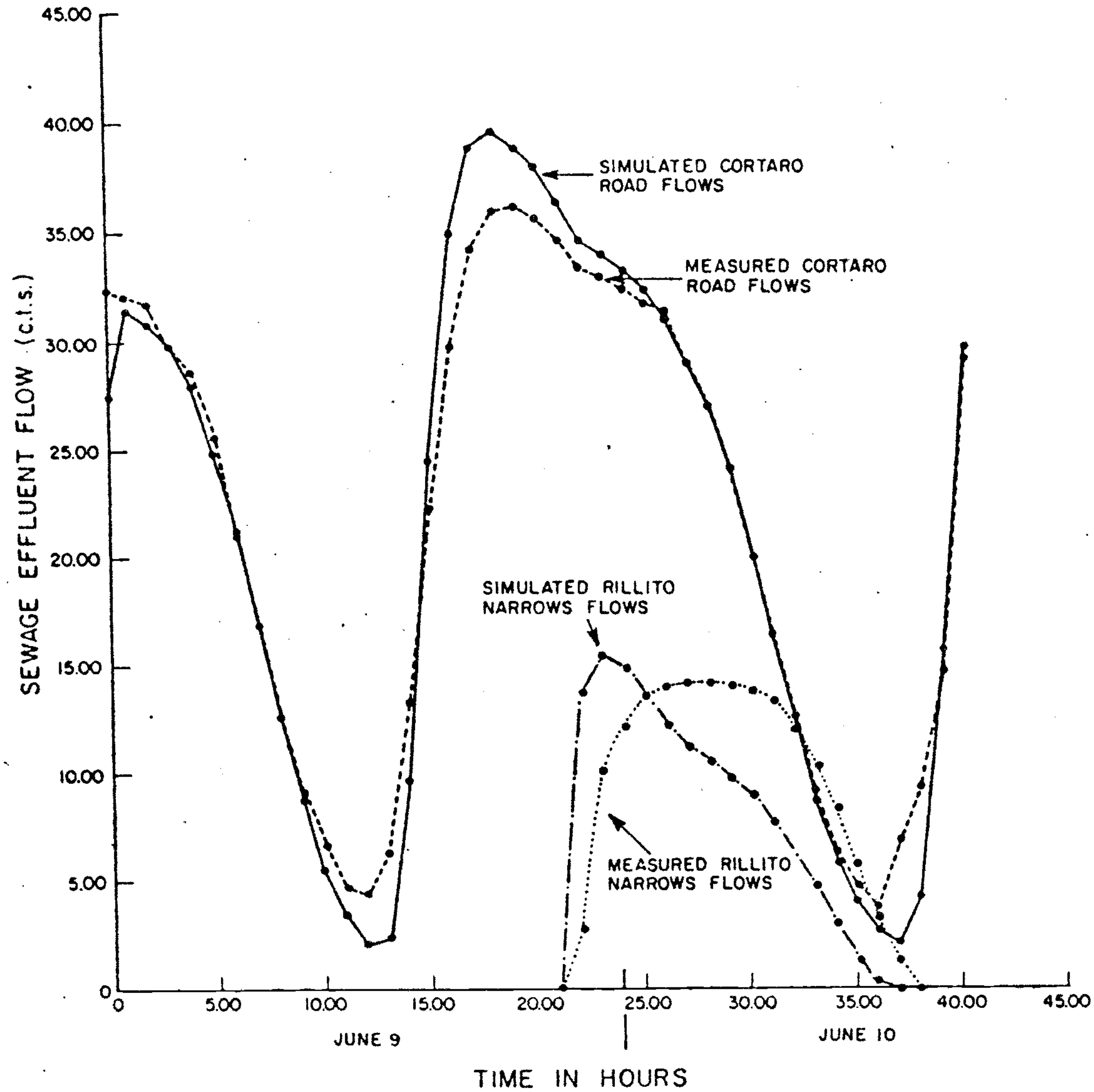


Figure 8. Comparison of Simulated and Measured Sewage Effluent Flows, Santa Cruz River, June 9-10, 1973.

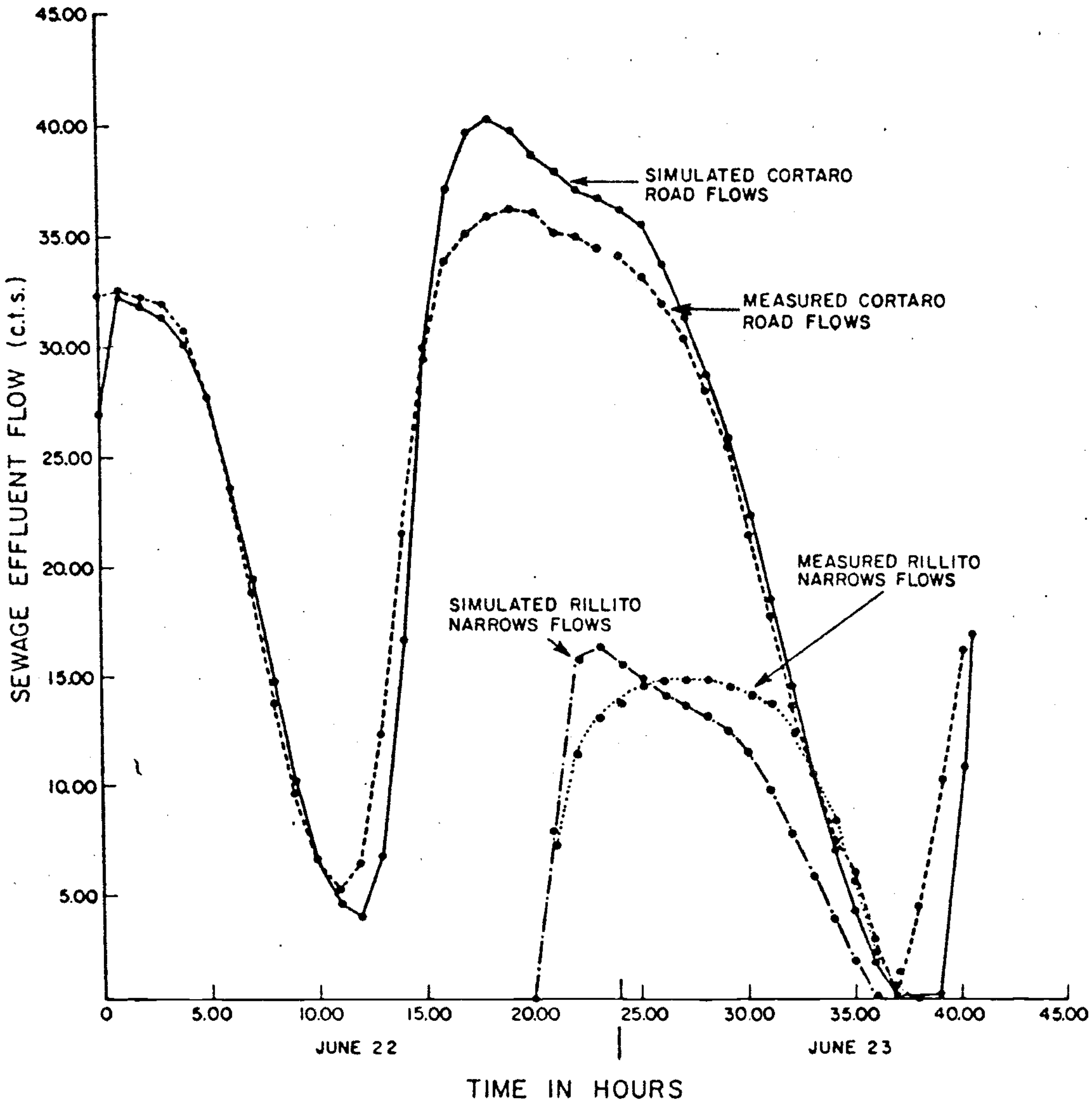


Figure 9. Comparison of Simulated and Measured Sewage Effluent Flows, Santa Cruz River, June 22-23, 1973.

In addition, similar anomalies of the peak flow and overall hydrographs at both stations are also found during this sample period which is characteristics of all other flow hydrographs. The deviations in the rising and declining limbs between measured and simulated effluent flow hydrograph are probably more extreme than any other sample period.

This close agreement between simulated and measured flow hydrographs at both flume stations for five sample periods is summarized in Table 3. It shows that, at both flume locations, the simulated peak flow is larger than the measured peak flows. In addition, the median relative error suggests that the approximate average error of peak flow measurements at Cortaro Road flume is larger than at Rillito Narrows, with values of 10% and 3%, respectively. Values of root mean square error also indicate that variances of peak flows at Cortaro Road are slightly greater than at Rillito Narrows flume.

In contrast to peak flows, the average error or water volume at Rillito Narrows is larger than at Cortaro Road flume, with 14% and 3%, respectively. The root mean square error at Rillito Narrows flume is also greater than at Cortaro Road. Therefore, the largest measurement error at Rillito Narrows is in total water volume.

It should be noted in Table 3 that, on June 26-27, 1973, flow rates and total water volume were much lower than the other four sample days with a corresponding large relative error, except at Rillito Narrows peak flow. In general, the channel losses seem to have been slightly underestimated in the reach TSTP to Cortaro, and overestimated between Cortaro and Rillito Narrows.

Simulated sewage effluent flow hydrographs at all eight established stations on the Santa Cruz River are shown in Figure 10 and 11. The simulated flow hydrograph (Figure 11) shows that the low flow disappeared at Pepper Tree Farm Road (approximately eight miles downstream), while observed low effluent flow continued as far as KOA Trailer Park (approximately nine miles downstream).

The difference between volumes gave the average infiltration rate per section. The mean flows and the average infiltration rate per given section are summarized in Table 4 for one sample period. The simulated flow data show that the largest incremental infiltration rate (5.6 cfs/mile) occurs between PCSTP and Cortaro Road. The smallest incremental infiltration rate (2.3 cfs/mile) occurs between Tucson Treatment Plant and Ruthrauff Road. It should be noted that these incremental infiltration rates represent varying conditions that occur within the measured stream sections. Additional flow measurements should be made to check the actual infiltration rates at various stream sections.

Comparison of measured and simulated sewage effluent flows and average sections infiltration rates for all sampling dates are summarized in Table 5. A comparison of the average measured channel losses for successive sections of the Santa Cruz River again indicates that the largest infiltration rate of 4.4 cfs/mile is between TSTP and Cortaro Road (Section 1), which is approximately 1.5 times the amount of effluent loss compared with the channel loss of 2.6 cfs/mile between Cortaro Road and Rillito Narrows (Section 2). Cluff et al. (1972) reported the largest infiltration rate (3.0 cfs/mile) occurred between Cortaro Road and the Rillito Narrows during similar sampling periods in June, 1972. Matlock (1965) also recorded an average infiltration rate of three

Table 3. Comparison of Peak Flow and Water Volume of Measured and Simulated Sewage Flows at Two Stations for Five Sample Periods.

Cortaro Road Flume -- 6.02 river miles donwstream from TSTP
Rillito Narrows Flume -- 11.27 river miles downstream from TSTP
Rel. Error -- relative error ((measured value - simulated value)/measured value)
RMSQE -- room mean squared error (standard deviation)
MRE -- median relative error

Sample Date	Cortaro Road Flume						Rillito Narrows Flume					
	Peak Flow (cfs)			Water Volume (ac-ft)			Peak Flow (cfs)			Water Volume (ac-ft)		
	Meas.	Sim.	Rel. Error (%)	Meas.	Sim.	Rel. Error (%)	Meas.	Sim.	Rel. Error (%)	Meas.	Sim.	Rel. Error (%)
6/9-10/73	36.4	39.7	- 9.1	46.9	48.3	- 3.0	14.3	15.6	- 9.1	13.6	11.2	+17.6
6/22-23/73	36.2	40.3	-11.3	50.8	52.3	- 3.0	14.9	16.3	- 9.4	15.6	13.6	+12.8
6/26-27/73	20.4	27.6	-35.3	28.0	33.2	-18.6	4.3	4.4	- 2.3	3.3	2.3	+30.3
7/3-4/73	40.7	45.2	-11.1	57.2	59.4	- 3.8	20.7	21.1	- 1.9	21.3	18.1	+15.0
7/5-6/73	39.9	42.7	- 7.0	56.7	58.2	- 2.6	18.3	18.9	- 3.3	19.8	18.2	+ 8.1
Mean	34.7	39.1	-12.7	47.9	50.3	- 5.0	14.5	15.3	- 5.5	14.7	12.7	+13.6
RMSQE			± 5.2			± 3.1			± 1.0			± 2.4
MRE (%)			10.0			3.0			3.0			14.0

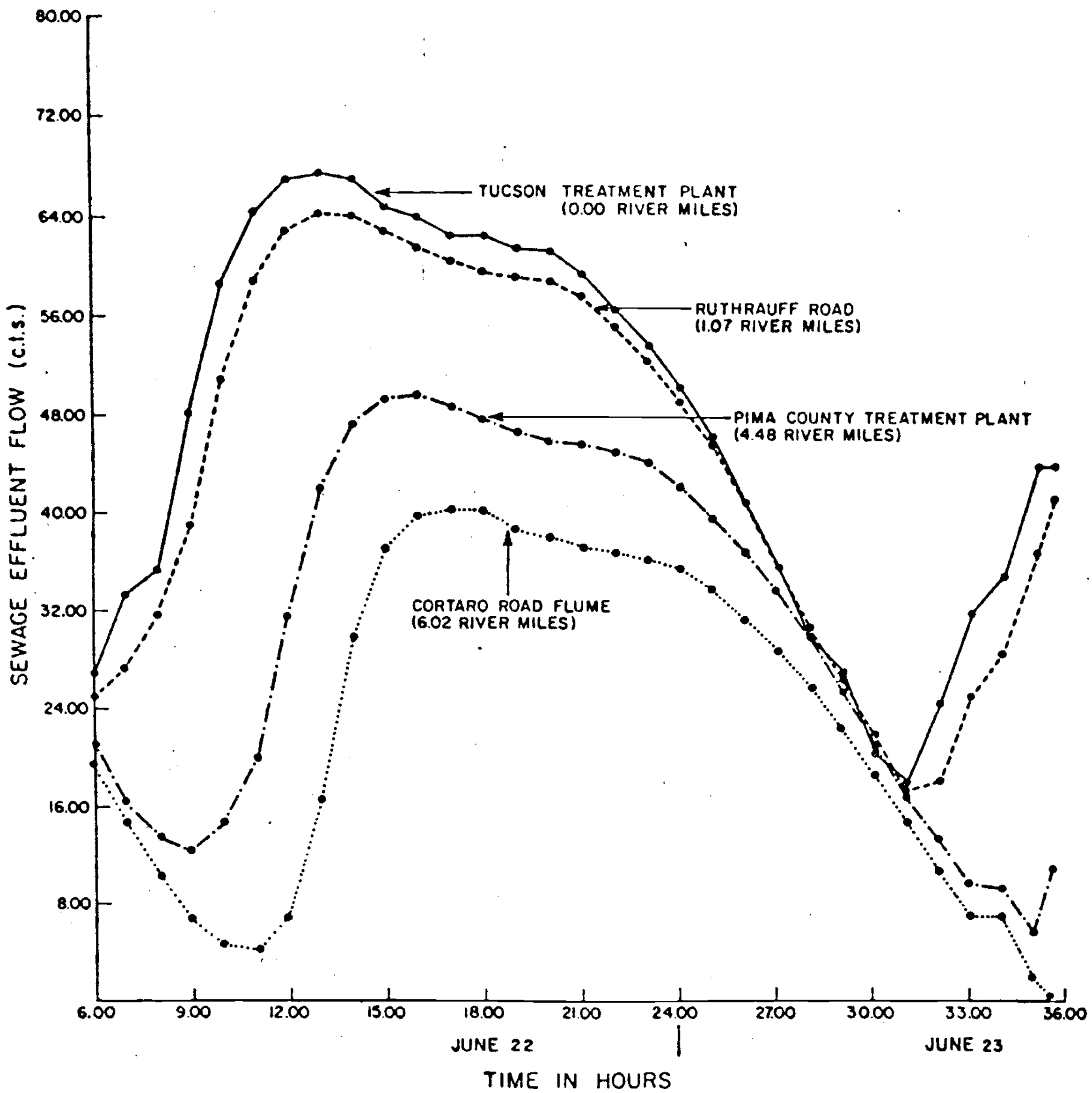


Figure 10. Simulated Sewage Effluent Flow Hydrographs Downstream, Santa Cruz River, June 22-23, 1973, between 0.00 and 6.02 River Miles.

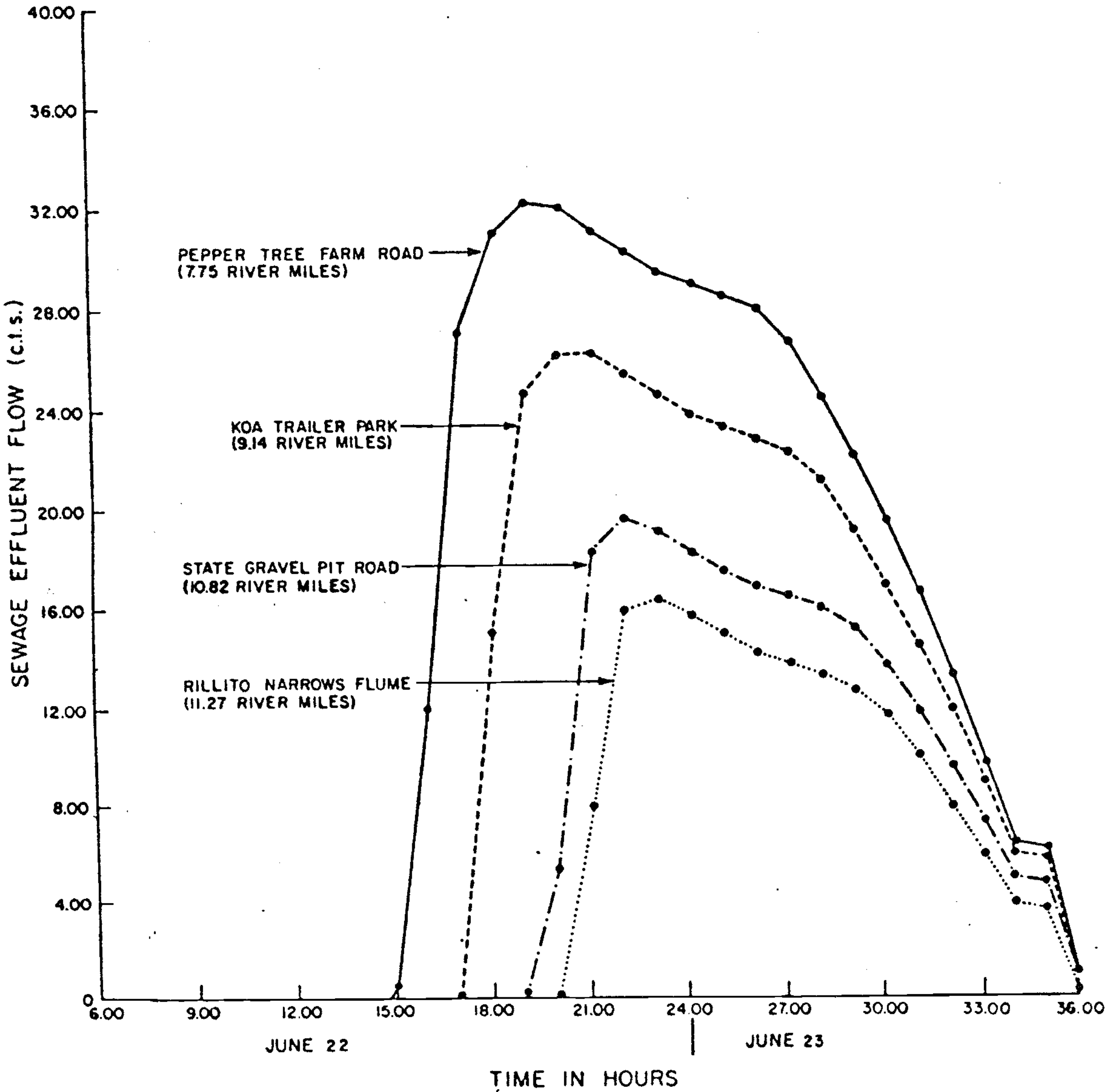


Figure 11. Simulated Sewage Effluent Flow Hydrographs Downstream, Santa Cruz River, June 22-23, 1973, between 7.75 and 11.27 River Miles.

Table 4. Simulated Mean Effluent Flows and Incremental Infiltration Rates, Santa Cruz River, June 22-23, 1973.

Stations	Distance Downstream (River Miles)	Mean Flow (cfs)	Average Infiltration Rate in Section (cfs/mile)
Tucson Sewage Treatment Plant	0.00	50.5	
			2.3
Ruthrauff Road	1.07	48.0	
			4.4
Pima County Sewage Treatment Plant	4.48	32.9	
			5.6
Cortaro Road Flume	6.02	24.3	
			2.6
Peppertree Farm Road	7.75	19.8	
			2.6
KOA Trailer Park	9.14	16.2	
			2.8
State Gravel Pit Road	10.82	11.3	
			2.9
Rillito Narrows Flume	11.27	10.0	

Table 5. Comparison of Measured and Simulated Sewage Effluent Flow and Average Sectional Infiltration Rates During Sampling Periods.

TSTP -- Tucson Sewage Treatment Plant (0.00 river mile)
Cortaro Road Flume (CRF) -- 6.02 river miles
Rillito Narrows Flume (RNF) -- 11.27 river miles
Section 1 -- between TSTP and CRF (6.02 miles)
Section 2 -- between CRF and RNF (5.25 miles)
Overall Reach -- between TSTP and RNF (11.27 miles)
Estimated infiltration loss in Santa Cruz River from Burkham (1970b), $Qf/mile = 0.11 (Q\ inflow)^{0.8}$

	Mean Flow (cfs)					Average Infiltration Rate in a Section (cfs/mile)								
	TSTP	CRF		RNF		Section 1			Section 2			Overall Reach		
Date	Meas.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Est.	Meas.	Sim.	Est.	Meas.	Sim.	Est.
6/9-10/73	49.1	23.6	23.4	9.4	8.2	4.2	4.3	2.8	2.7	2.9	2.8	3.5	3.6	2.8
6/22-23/73	50.5	23.7	24.3	10.2	10.0	4.5	4.4	2.8	2.6	2.7	2.8	3.6	3.6	2.8
6/26-27/73	42.3	13.5	17.9	3.3	2.3	4.8	4.1	2.4	1.9	2.1	2.4	3.5	3.5	2.4
7/3-4/73	54.3	28.8	29.2	13.2	12.5	4.2	4.2	3.0	3.0	3.1	3.0	3.6	3.7	3.0
7/5-6/73	54.9	28.6	29.3	13.0	12.6	4.4	4.2	2.9	3.0	3.2	2.9	3.7	3.8	2.9
Average	50.2	23.6	24.8	9.8	9.1	4.4	4.2	2.8	2.6	2.8	2.8	3.6	3.6	2.8

cfs/mile for the section of river above Cortaro Road after a major flow event. The discrepancies in average infiltration loss rates between the various studies could be due to changes in streambed composition and geometry between the sampling periods.

Measured and simulated sewage effluent losses were also compared with the general empirical infiltration equation developed by Burkham (1970b). He found that average infiltration per mile for the Santa Cruz River and Rillito Creek was as follows:

$$Q\ (\text{infiltration})/\text{mile} = 0.11\ (Q\ \text{inflow})^{0.8}$$

This equation was then used to determine average channel loss rate in a section (cfs/mile) for each measured reach. It was assumed that average daily discharges from TSTP represented inflow into the Santa Cruz River as indicated by the empirical equation.

Results showed that, in Section 1, the average channel loss rate using Burkham's method was 2.8 cfs/mile, compared with the measured and simulated values of 4.4 and 4.2 cfs/mile, respectively. In Section 2, close agreement was found between measured, simulated and the empirical infiltration rates with values of 2.6, 2.8 and 2.8 cfs/mile, respectively. Therefore, overall empirical equations as derived by Burkham (1970b) may be an adequate estimate of average daily infiltration rates in particular stream sections, where the conditions have not changed.

Chemical Species Parameters

Typical measured and predicted curves of organic nitrogen, ammonia nitrogen, nitrate nitrogen and total nitrogen concentrations versus distance are presented in Figures 12, 13, 14 and 15, respectively. The hydraulic parameters obtained from the kinematic-wave model, and the physicochemical values from the last two sample periods -- July 3-4 and July 5-6, 1973 -- were used in the nitrogen transformation model and the outputs compared with the measured values for nitrogen species transformations within sewage effluent releases as flow proceeds downstream. The overall nitrogen species trends during indicated sample days show that organic nitrogen, ammonia nitrogen and total nitrogen have measured values greater than predicted values at low effluent flows. However, at high effluent flows these same nitrogen species have predicted values greater than measured values. Since the initial conditions of organic nitrogen, ammonia nitrogen and total nitrogen at TSTP and PCSTP, which are discharge points, are fairly consistent over the two sampling periods, it can be concluded either that other chemical parameters such as suspended solids, temperature and dissolved oxygen, or hydraulic parameters such as cross-sectional area and velocity may be important. It is hypothesized that a combination of cross-sectional area, velocity and suspended solids values affect the predicted measurements of organic nitrogen, ammonia nitrogen and total nitrogen between low and high effluent flows, since transport capacity of sediment is directly related to spreading area and velocity. The other physicochemical parameters may greatly affect the complex biological system of the effluent

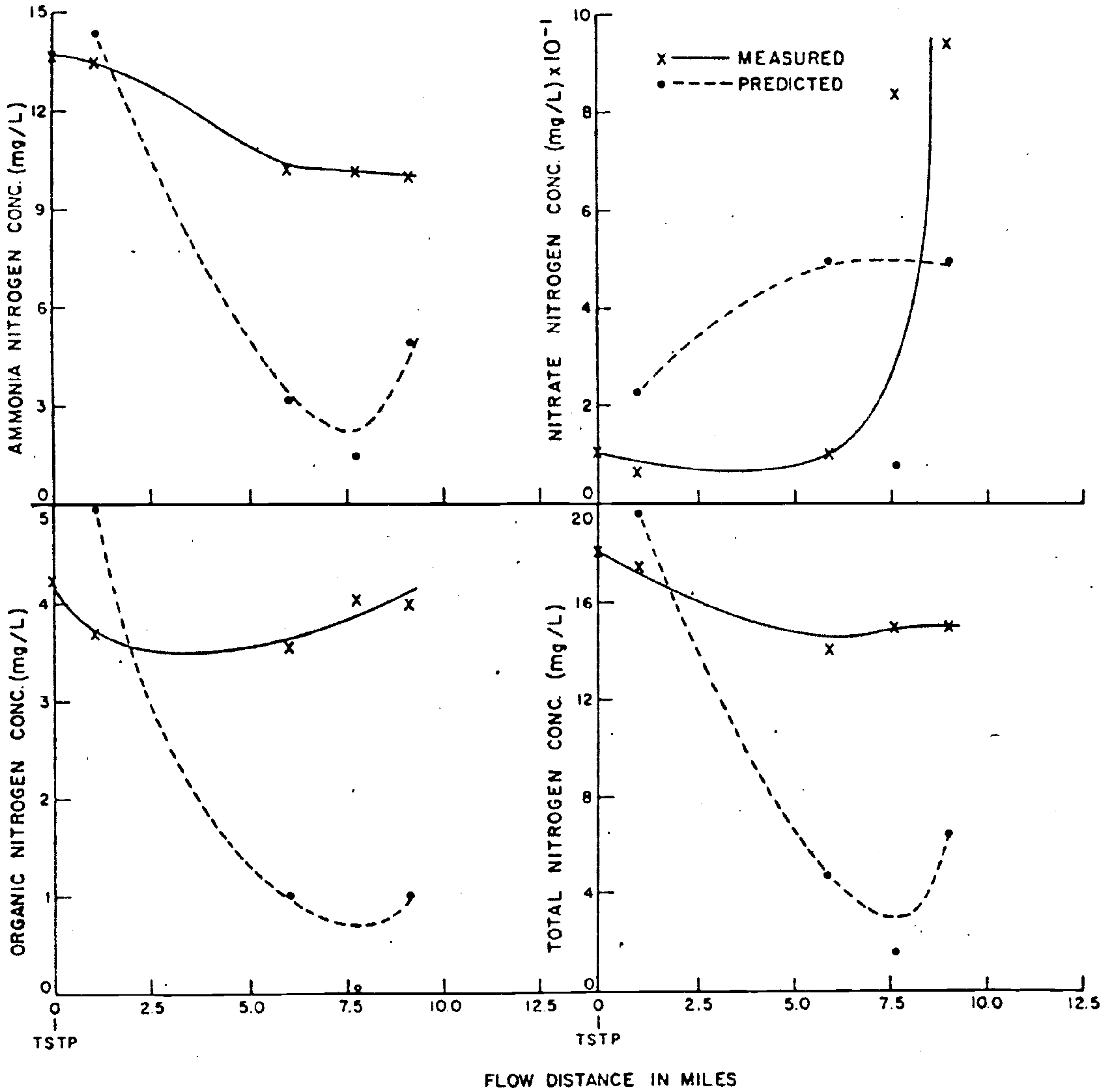


Figure 12. Measured and Predicted Nitrogen Transformations in Effluent During Low Flow, July 3-4, 1973.

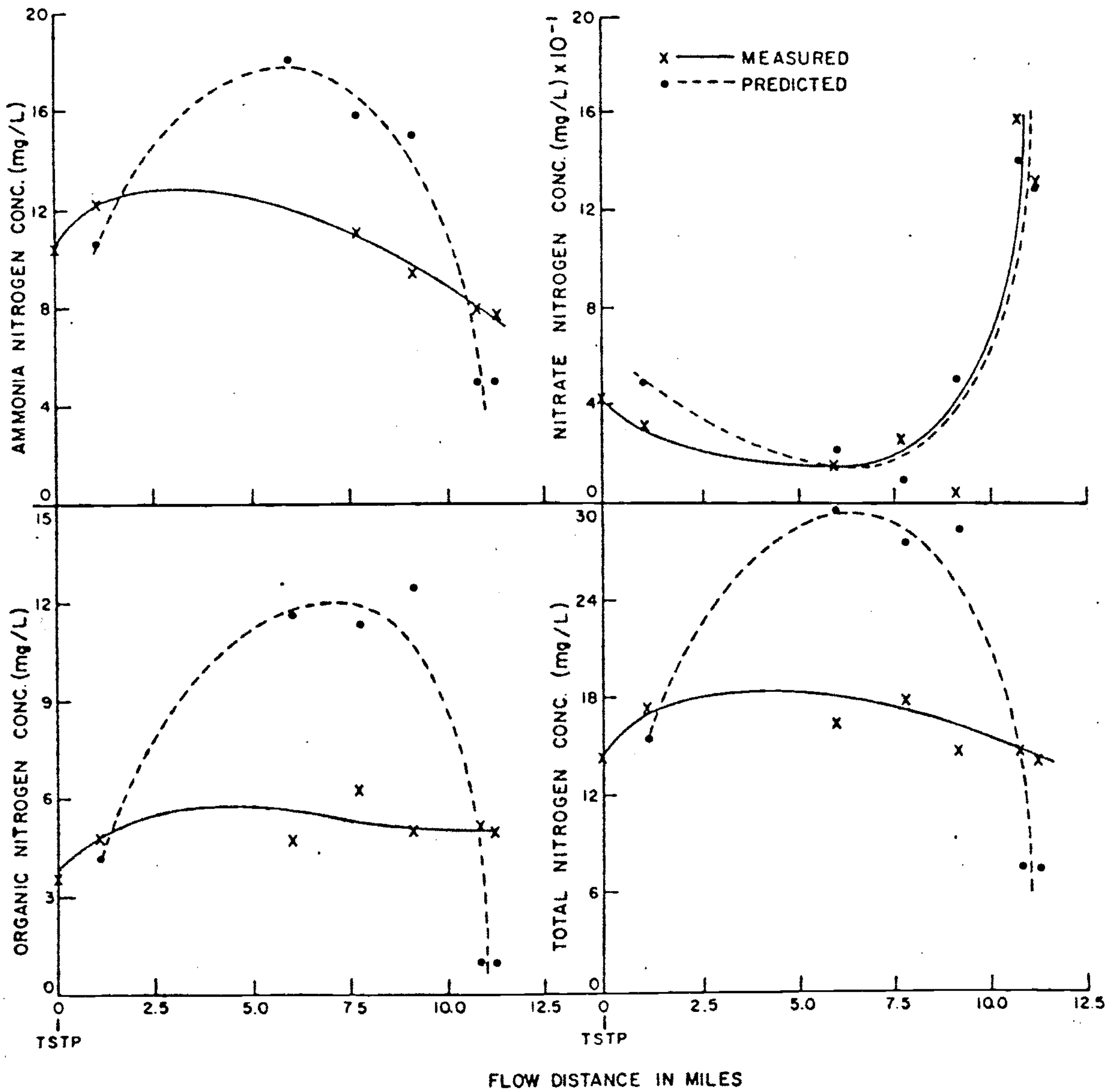


Figure 13. Measured and Predicted Nitrogen Transformations in Effluent During High Flow, July 3-4, 1973.

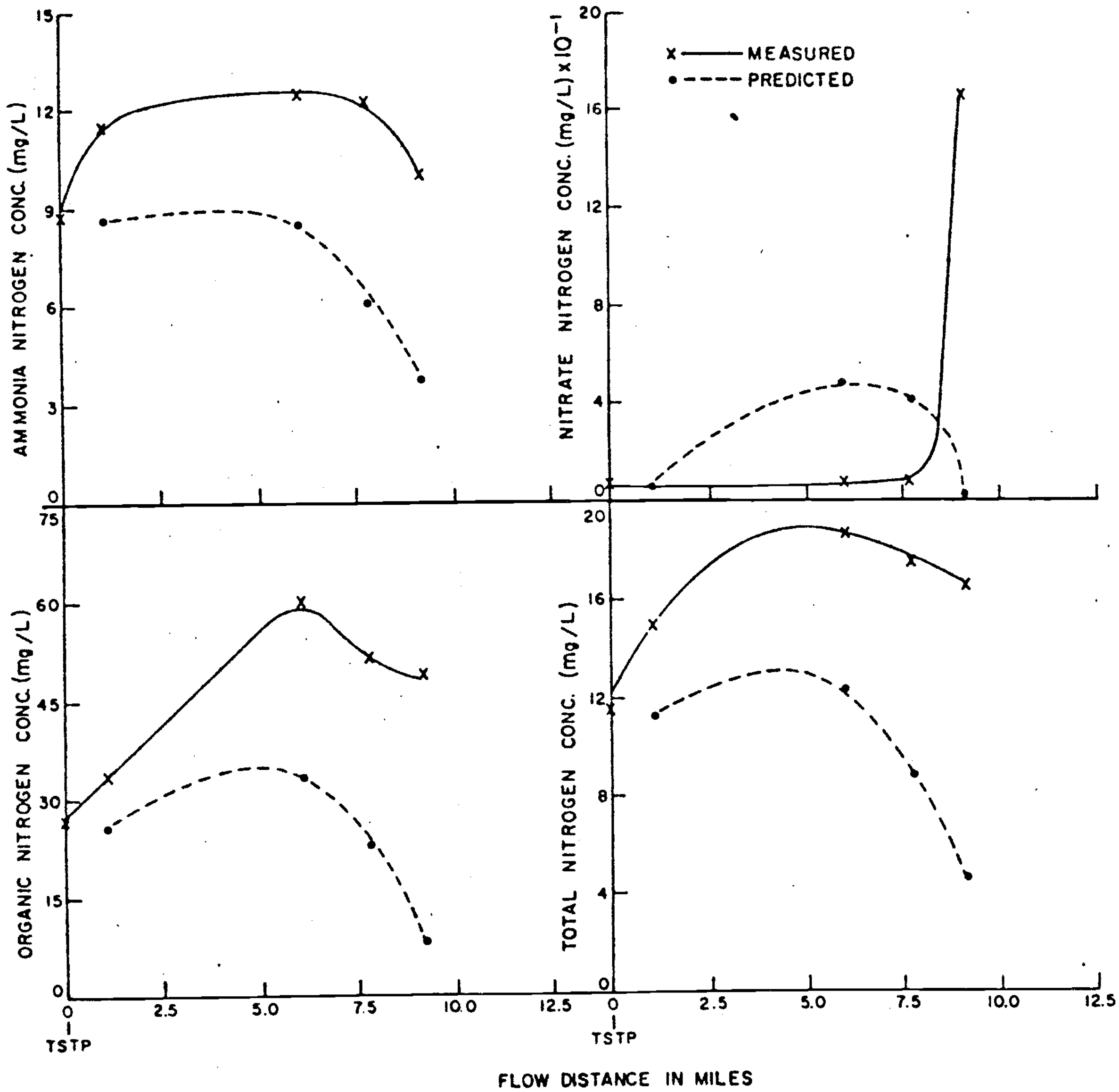


Figure 14. Measured and Predicted Nitrogen Transformations in Effluent During Low Flow, July 5-6, 1973.

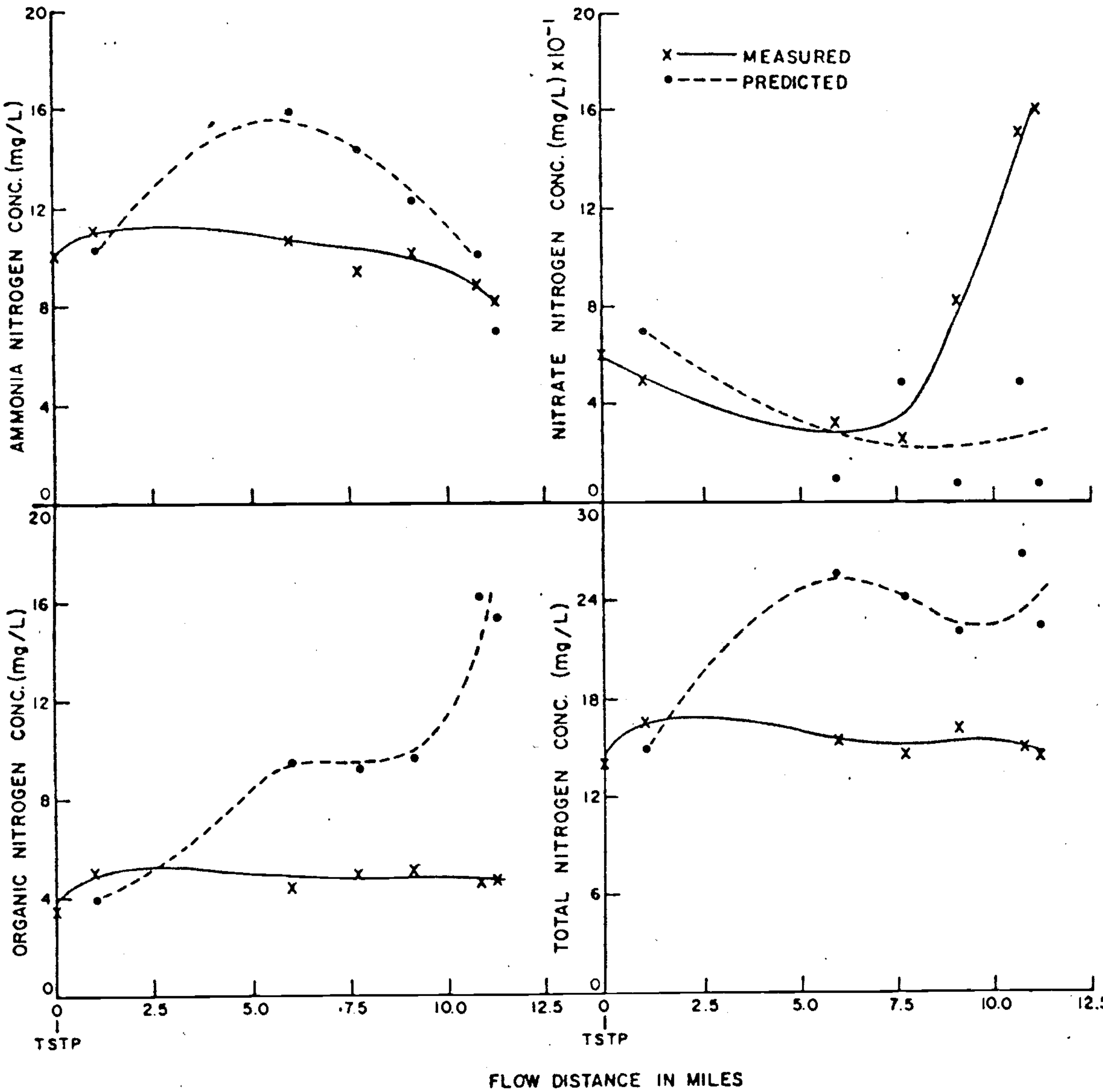


Figure 15. Measured and Predicted Nitrogen Transformations in Effluent During High Flow, July 5-6, 1973.

stream environment through complicated and unmodelled interactions.

Measured and predicted values of nitrate nitrogen, compared at low and high effluent flows, had a more complex relationship. At both low and high effluent flows during the two sample periods, predicted nitrate nitrogen values were greater than measured values from the TSTP to approximately Cortaro Road flume (about 6 river miles downstream). However, after this sampling location, measured values were greater than predicted nitrate nitrogen values. Measured nitrate values indicated that very rapid nitrification occurred approximately between Cortaro Road and Pepper Tree Farm. This rapid rate of nitrification was not reflected in the predicted nitrate values, except during high flow on July 3-4, 1973 (Figure 13), because of the undetermined interrelationship between pH and velocity of effluetn. Statistical analysis consisting of relative error (%), standard error estimate (SEE) and correlation coefficient (R), using least squares method were used to compare measured versus predicted nitrogen species values as well as overall accuracy of nitrogen transformation model. As shown in Table 6, which sums by sample locations the measured and predicted nitrogen species values in the sewage effluent releases and in Table 7, which sums by sample times by the same parameters, fair to poor prediction occurs between all measured and predicted nitrogen values. The poor results of predicted organic nitrogen values is attributed to the following: (1) inconsistent ammonification rate ($R^2 = 0.368$), as shown in procedures, (2) large unaccountable biological mechanisms and conversions, and (3) unaccountable sedimentation and coagulation processes. These conclusions are reaffirmed by Velz (1970) who indicates that the organic fraction and its conversions depend upon: amount of settlable solids, flocculation or coagulation of colloids and nonsettlable solids, and biological extraction and accumulation. He also states that velocity and channel characteristics play important role in organic nitrogen concentration. However, no exact determination of the complicated mechanisms were attempted. Comparison of measured and predicted ammonia nitrogen concentrations in Tables 6 and 7 show a more consistant correlation coefficient than organic nitrogen values. However, ammonia nitrogen concentrations are related directly with organic nitrogen concentration through the ammonification rates causing the predicted ammonia nitrogen concentration to be exceedingly variable. In addition, algae utilization rates as given by O'Connor et al. (1973) were used on the calibration trials and found to be very insignificant. Possibly, under ideal conditions, such as Arizona summers, the algae utilization rates may be greater and therefore significant in reducing ammonia concentrations. However, ammonia nitrogen pathways are extremely complex mechanisms under natural conditions which cannot be accurately accounted for within the model.

Correlation coefficients between measured and predicted nitrite-nitrate nitrogen values show some consistency. It was assumed, in the nitrogen transformation model, that nitrification process was the direct conversion of ammonia nitrogen to nitrate nitrogen; whereas in reality, nitrification is a two-step series conversion ($NH_3N \rightarrow NO_2N \rightarrow NO_3N$). In addition, each conversion step is not always synchronized since each group has a different response at various environmental conditions. Therefore, nitrate nitrogen concentration would increase as the overall nitrification rate increases, which may not represent the actual speed of the reaction. Velz (1970) states that a

Table 6. Verification Results Summed by Sample Locations of Measured and Predicted Nitrogen Species Values in Sewage Effluent Releases for Two Sample Days, Santa Cruz River.

Meas. = measure concentrations.
Pred. = predicted concentrations.
SEE = standard error of estimate.
R = correlation coefficient.

TSTP = Tucson Sewage Treatment Plant.
* = nitrogen values shown are summed by downstream location with respect to each initial sampling time.

Date	Initial Sampling Time at TSTP (hours)	Organic Nitrogen Mean* Meas. (mg/l)	Organic Nitrogen Mean* Pred. (mg/l)	Organic Nitrogen SEE	Organic Nitrogen R	Ammonia Nitrogen Mean* Meas. (mg/l)	Ammonia Nitrogen Mean* Pred. (mg/l)	Ammonia Nitrogen SEE	Ammonia Nitrogen R	Nitrate Nitrogen Mean* Meas. (mg/l)	Nitrate Nitrogen Mean* Pred. (mg/l)	Nitrate Nitrogen SEE	Nitrate Nitrogen R	Total Nitrogen Mean* Meas. (mg/l)	Total Nitrogen Mean* Pred. (mg/l)	Total Nitrogen SEE	Total Nitrogen R
July 3-4, 1973	07:30	3.8	1.8	1.7	-.46	11.1	6.0	1.4	+.96	0.5	0.3	0.2	-.12	15.5	8.1	3.2	+.88
	10:00	5.8	7.6	3.0	+.90	10.6	11.8	2.9	+.91	0.6	0.5	0.2	+.43	16.9	19.9	3.7	+.96
	14:30	5.2	7.0	4.9	+.21	10.1	11.7	3.6	+.72	0.6	0.7	0.2	+.93	15.9	19.3	8.6	+.45
	21:00	4.2	21.1	7.5	-.15	10.6	23.7	6.0	+.29	0.3	2.5	0.9	+.60	15.2	47.4	11.6	-.76
	04:00	5.0	11.8	2.7	+.26	12.2	23.6	3.3	+.19	0.7	0.9	0.2	+.97	17.8	36.3	4.2	-.43
July 5-6, 1973	07:30	4.9	2.2	0.9	+.20	11.7	6.8	1.3	+.75	0.5	0.2	0.2	-.61	17.1	9.3	2.9	+.16
	10:00	5.8	12.3	7.6	-.57	10.7	8.3	1.6	+.81	0.8	0.6	0.2	+.78	17.3	21.2	5.6	-.72
	14:30	4.9	10.7	3.8	-.41	9.9	11.8	2.4	+.56	0.9	0.3	0.2	-.22	15.6	22.8	2.8	-.69
	21:00	5.0	14.3	3.7	-.48	12.4	14.6	2.9	+.91	0.3	1.9	0.5	-.88	17.8	30.8	7.8	-.12
	04:00	5.3	14.9	3.3	+.74	11.9	16.8	2.5	-.71	0.4	0.9	0.2	+.93	17.6	32.5	7.5	+.66

Table 7. Verification Results Summed by Sample Times of Measured and Predicted Nitrogen Species Values in Sewage Effluent Releases for Two Sample Days, Santa Cruz River.

Meas. = measure concentrations.
Pred. = predicted concentrations.
SEE = standard error of estimate.
R = correlation coefficient.
TSTP = Tucson Sewage Treatment Plant.
* = nitrogen values shown are summed by sampling times within a daily hydrograph period with respect to each sampling location.

RRR = Ruthrauff Road (1.07 river miles).
CRF = Cortaro Road Flume (6.02 river miles).
PTF = Peppertree Farm (7.75 river miles).
KOA = KOA Trailer Park (9.14 river miles).
GPS = Gravel Pit State (10.82 river miles).
RNF = Rillito Narrows Flume (11.27 river miles).

		Organic Nitrogen				Ammonia Nitrogen				Nitrate Nitrogen				Total Nitrogen			
Date	Sampling Location	Mean* Meas. (mg/1)	Mean* Pred. (mg/1)	SEE	R	Mean* Meas. (mg/1)	Mean* Pred. (mg/1)	SEE	R	Mean* Meas. (mg/1)	Mean* Pred. (mg/1)	SEE	R	Mean* Meas. (mg/1)	Mean* Pred. (mg/1)	SEE	R
July 3-4, 1973	RRR	5.9	5.1	1.1	-.38	14.0	13.2	1.2	+.97	0.2	0.5	0.4	-.14	18.4	20.5	1.8	+.94
	CRF	9.8	10.0	7.2	+.13	14.2	17.6	9.1	+.43	0.1	0.5	0.3	-.72	16.9	30.9	16.8	+.22
	PTF	8.8	9.3	7.0	+.12	13.1	14.4	8.6	+.43	0.3	0.6	0.6	-.43	17.0	30.6	16.7	+.09
	KOA	6.7	9.3	5.0	+.72	11.4	11.0	7.1	+.45	0.6	1.1	0.8	-.21	16.7	33.1	13.1	+.51
	GPS	4.2	5.6	11.0	-.33	13.4	5.6	3.5	+.92	1.3	2.0	1.2	-.42	15.4	27.5	19.9	+.35
	RNF	3.7	5.7	7.9	-.60	7.5	9.5	6.9	-.21	1.0	1.9	0.8	-.79	12.6	20.9	15.1	-.50
July 5-6, 1973	RRR	4.7	4.0	0.9	+.30	12.1	10.8	1.0	+.90	0.2	0.3	0.1	+.94	17.0	15.2	1.4	+.90
	CRF	5.2	10.1	3.8	-.70	12.8	16.3	5.8	+.18	0.2	0.5	0.3	-.51	18.1	26.9	11.2	-.16
	PTF	5.5	9.3	4.4	-.17	12.5	13.2	4.6	+.17	0.1	0.7	0.3	-.66	18.1	23.2	9.4	+.11
	KOA	5.4	10.1	5.4	-.30	10.9	12.0	2.6	+.88	0.9	0.7	0.6	-.77	17.2	22.7	11.1	-.28
	GPS	5.2	19.5	3.5	+.50	9.3	10.8	3.8	+.22	1.2	1.3	0.5	-.90	15.7	31.8	4.8	-.19
	RNF	5.2	19.3	3.3	-.30	9.3	7.8	3.8	+.72	1.3	1.5	0.5	-.89	15.8	28.6	5.1	+.62

substantial difference in sensitivities of nitrifying bacteria to environmental condition results in abnormalities of nitrification. Courchaine (1963) described and analyzed a reach of the Grand River below the Lansing, Michigan, activated-sludge treatment plant, and found that nitrification reactions rates were extremely variable.

Large errors in predicted total nitrogen values and inconsistent correlation coefficients between measured and predicted total nitrogen values are caused by the combined effect of large predicted values of organic nitrogen, ammonia nitrogen and nitrate nitrogen. Overall, the nitrogen transformation model is a fair to poor prediction of measured nitrogen concentrations in sewage effluent flows. Basic improvements in the model, such as assuming a first-order reaction rate between nitrogen species, would be more representative of the actual environmental conditions. In addition, biological conversion and incorporation of ammonia nitrogen and biological and physical extraction of organic nitrogen should also be included within the model. Finally, an integrated system of nitrogen species balancing should be also incorporated so that extraneous nitrogen concentrations can be removed from the model.

Nitrogen Transformations in Sewage Effluent

The transformations of the various nitrogen species in sewage effluent during high and low flows at two different sample periods are related to flow distance as shown in Figures 16 and 17. Measured organic nitrogen values are relatively constant at the two flow conditions during the two sampling periods. It should be noted that, at Ruthrauff Road, below an effluent discharge point, slight increases in organic nitrogen concentrations were found at high flows. Supernatant and digested sludge is added to the effluent during certain stages in operation of the Tucson Sewage Treatment Plant. These benthic organic particles are then picked up and transported down the stream channel by sewage effluent flow. Therefore, changes in measured organic nitrogen content at Ruthrauff Road are probably caused by scour action on benthic deposits by effluent flows. Below the PCSTP oxidation ponds, an effluent discharge point, increased organic concentrations were released to the effluent flow during particular pond cycles reflecting in increased organic concentration immediately downstream.

Ammonia nitrogen concentrations also increase at both Ruthrauff Road and below PCSTP due to these unusual effluent discharges. However, ammonia nitrogen did decrease significantly after Cortaro Road flume section (6.02 river miles).

Ammonia nitrogen decreases are essentially caused by the conversion of ammonia nitrogen to nitrate nitrogen by the nitrification process. In addition, other factors such as ammonia volatilization, fixation on clay and organic particles, and microbial incorporation may have a significant effect on ammonia nitrogen losses under different environmental conditions.

Results of water quality samples also show that nitrate nitrogen concentration increases as flow distance increases, with the highest nitrate nitrogen concentrations at Rillito Narrows (11.27 river miles). Sebenik et al. (1972)

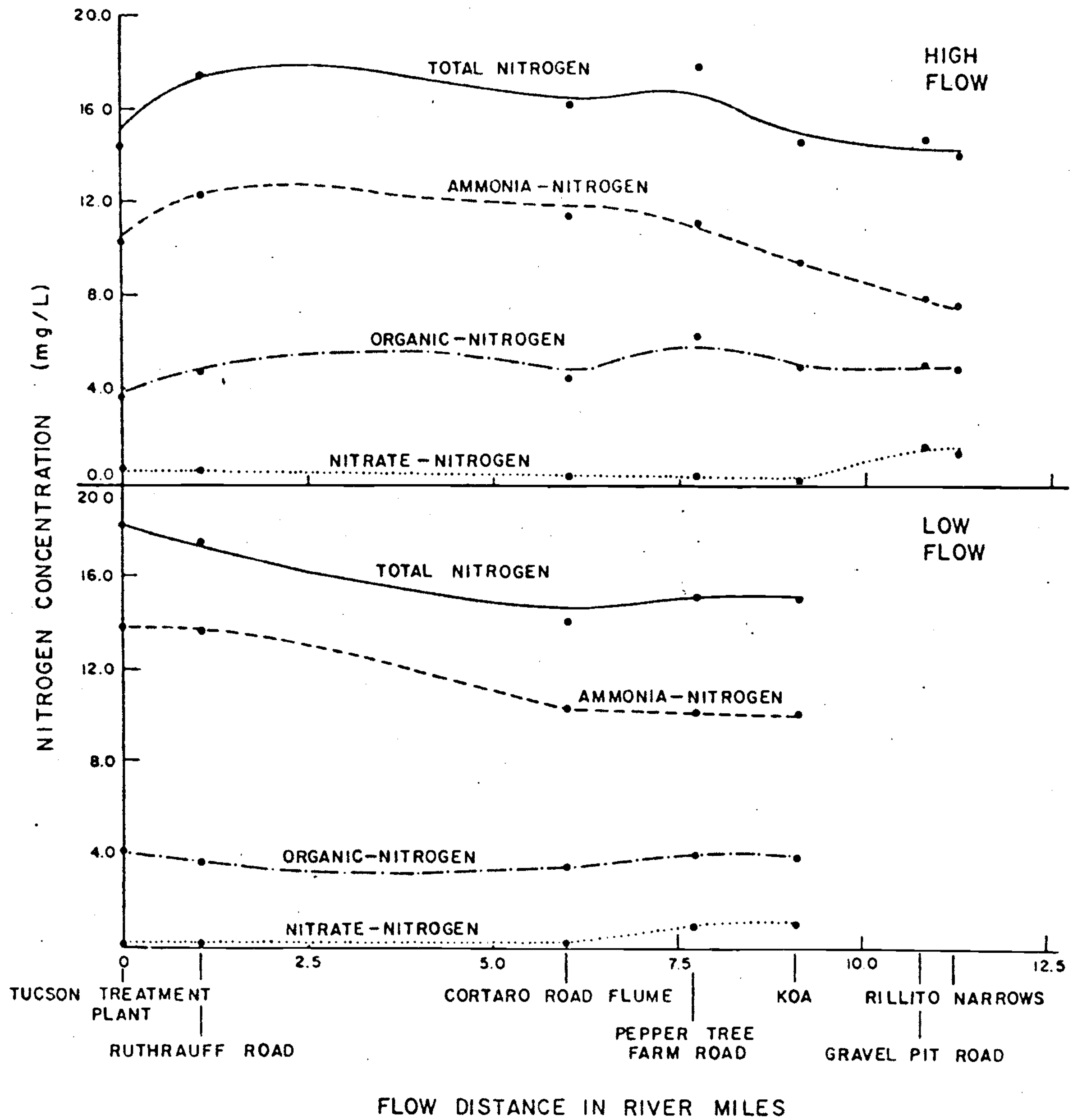


Figure 16. Nitrogen Transformations in Effluent During High and Low Flows, July 3-4, 1973.

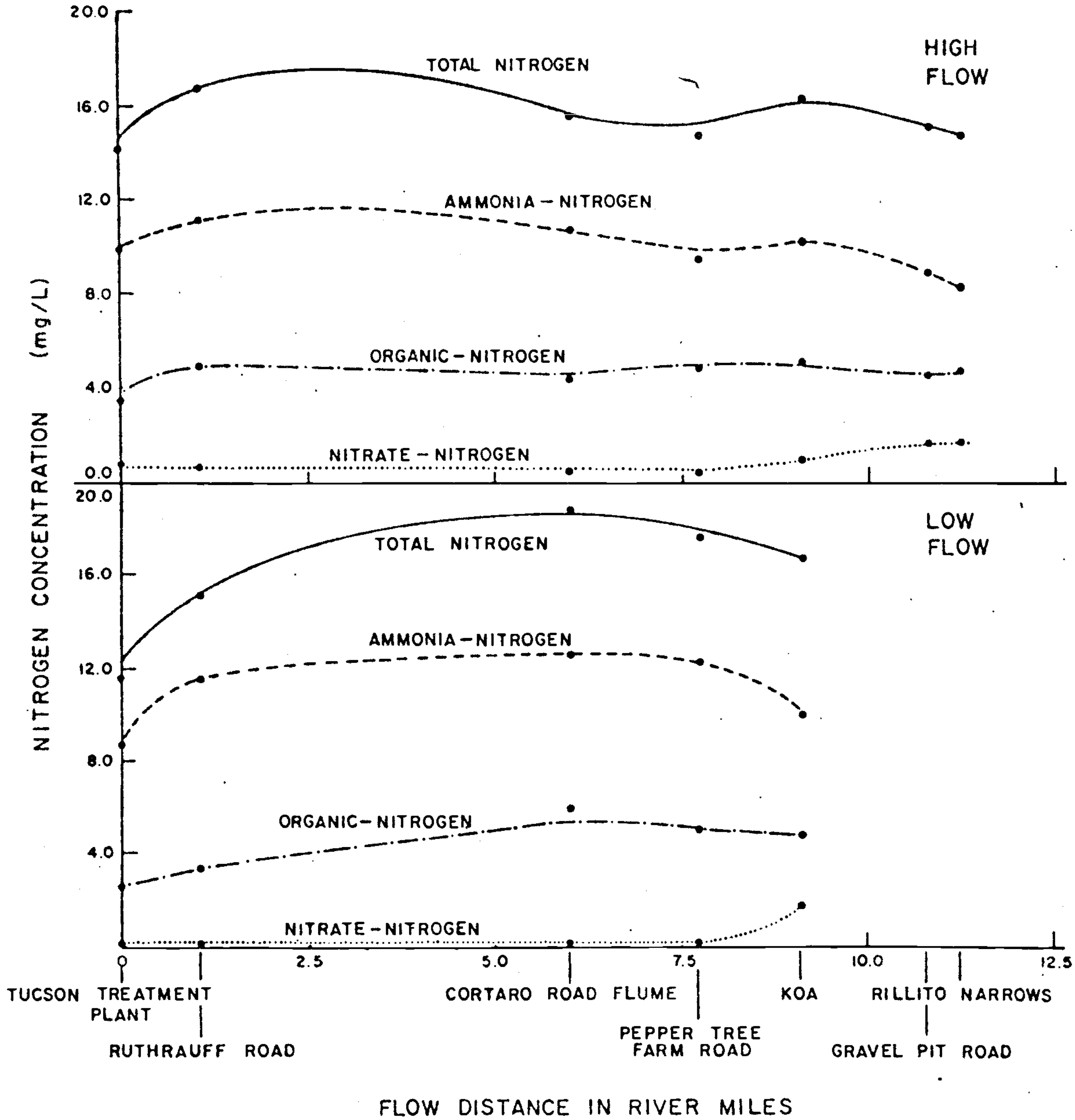


Figure 17. Nitrogen Transformations in Effluent During High and Low Flows, July 5-6, 1973.

reported similar nitrification results. It should be noted that nitrification increases are associated with widening streambed areas and reduced effluent velocities. It is assumed that increased surface area permits increasing effluent contact with nitrifying bacteria within the streambed material causing the nitrification rate to increase. Complicated processes of effluent arrival times at various stream sections in relation to air and water temperatures and time of day may also have large effect in the nitrification processes.

SUMMARY AND CONCLUSIONS

Summary

Sewage effluent flows from the Tucson Sewage Treatment Plant (river mile 0.0) have been released down the dry Santa Cruz River for a period of ten years, causing possible increases in nitrate nitrogen concentration in the groundwater supply. Two effluent flow measurement stations with automatic recorders were installed at Cortaro Road (6.02 river miles) and at Rillito Narrows (11.27 river miles). Flow measurements were made at both flume stations and at TSTP and PCSTP from May 30 to July 9, 1973, to determine the amount of actual channel losses occurring at various stream sections. During this time, five representative sample periods were selected for a detailed water quality sampling program. Water quality samples were taken at established locations in sequence, and at various stages as the effluent surge moved downstream. Physicochemical parameters, consisting of field pH, field temperature and dissolved oxygen, were taken <u>in situ</u>. Water quality samples were analyzed in the laboratory for suspended solids, total solids, chemical oxygen demand, carbonate, bicarbonate, chloride, organic nitrogen, ammonia nitrogen and nitrate nitrogen. These various physicochemical parameters were used as important constituents in water quality modelling of nitrogen transformations.

A kinematic-wave model was adapted to simulate effluent flow hydrographs and to determine channel losses. Close agreement was found between simulated and measured flow hydrographs at both flume stations. Average measured sectional infiltration rates are 4.2 cfs/mile between Cortaro Road and Rillito Narrows.

Hydraulic parameters obtained from the kinematic-wave model and measured physicochemical values were used as variables in a nitrogen transformation model to predict organic nitrogen, ammonia nitrogen, and nitrate nitrogen transformations with sewage effluent releases during their downstream progress. The nitrogen transformation model used a kinetic-multiple regression approach to simulate the nitrogen pathways. Each pathway was quantified by a preliminary rate equation developed using computerized multiple regression analysis from collected data. The nitrogen transformation model, as developed here, was found to be a poor predictor of organic nitrogen concentration in sewage effluent flow due to the unaccounted effects of sedimentation, coagulation, stream scour and microbial conversion. Predicted ammonia nitrogen and nitrate nitrogen concentrations were found to be within a more acceptable range. To yield better results, nitrate nitrogen concentration should be modelled in a two-step series conversion to account for both populations of <u>Nitrosomonas</u> and <u>Nitrobacter</u> bacteria. Basic improvements in the nitrogen transformation model could be made by: (1) assuming first-order reaction rates between nitrogen species, (2) including biological conversion and incorporation of ammonia nitrogen, (3) including sedimentation and flocculation process, and (4) providing an integrated system of nitrogen species balancing.

Measured nitrogen species versus flow distance were also compared. It was found that organic nitrogen concentrations were generally uniform, and nitrate nitrogen increased as the flow proceeded downstream, indicating nitrification. The rate of nitrification in sewage effluent releases is related to flow distance and the physical characteristics of the stream, with the nitrification and denitrification process evidently occurring together in the moving stream.

Comprehensive Aspects of the Project

Generally, two important interrelated aspects of the physicochemical transformation of sewage effluent releases in an ephemeral stream channel are the following: (1) hydraulic and (2) physicochemical. The hydraulic aspects involved the natural recharge of the Tucson Basin aquifer by sewage effluent which amounts to about 28,000 acre-feet per year or 80 percent of total effluent releases at TSTP as measured in this study. As noted by Matlock et al. (1972), and Schmidt (1973), groundwater levels in the Cortaro area are now relatively stable even with large irrigation pumpages indicating the excellent rechargeability of the aquifer by continued sewage effluent flows.

The physicochemical aspects of sewage effluent releases could have a detrimental effect upon the domestic water pumped from the area by increasing nitrate concentrations and possibly enteric viruses. Increases in nitrate content in the Cortaro area wells during the period of 1970 to 1972 ranged from 36 to 133 percent and average 66 percent. These increases are attributed to the increasing amount of sewage effluent percolating into the alluvial channel (Schmidt, 1973). Therefore, groundwater degradation is very likely related to disposal of sewage effluent in the alluvial stream channels.

The interrelationship between the sinusoidal properties of the effluent hydrograph, the physicochemical properties of the effluent and the increased nitrate concentration in groundwater are also important. The effluent flow fluctuations in the lateral and longitudinal directions flush the soil water with high nitrate concentrations into perched water tables. Soil nitrification has the greatest effect at the extremities of effluent flows since the reaction rate, drying time and microbial conversion by nitrifers is maximized. In addition, increased infiltration rates at these same areas cause abnormal amounts of highly nitrated soil water to be added to the perched water table. The stream channel areas with these described conditions also have the maximum wetted surface area at high effluent flows. A typical example of such channel areas is between Ina Road (river mile 5.0) and Pepper Tree Farm Road (river mile 8.0), where areal fluctuations may vary from 40 to 80 feet in width between low and high effluent flows. In addition, nitrate concentrations of groundwater samples within this approximate area (near Cortaro Road) are above normal (exceeding 90 ppm), indicating a relationship between wetted area, infiltration, nitrification and groundwater quality. However, the effluent quantity and quality relationships are exceedingly complex; the complications become an order of magnitude greater when the effects of the groundwater system are considered.

Conclusions

1. Close agreement was found between simulated and measured effluent flow hydrographs at two established stations in the Santa Cruz River, using a modified kinematic-wave model.

2. Infiltration rates of 4.2 cfs/mile and 2.6 cfs/mile were measured in consecutive stream sections.

3. The developed nitrogen transformation model, as a predictor of the various nitrogen species present in the sewage effluent at various stream sections, needs improvement.

4. The rate of nitrification in sewage effluent releases is related to flow distance and the physical characteristics of the stream.

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